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(NASA-CR-173065) NASA'S SPACE RESEARCH AND
TECHNOLOGY PROGRAM. REPORT OF A WORKSHOP
Final Report (National Academy of Sciences -
National Research) 129 p HC A07/MF A01;
also available from Aeronaut

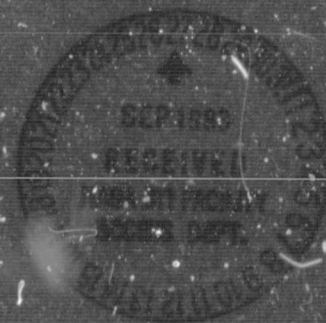
N83-33916

CSCI 22A G3/12

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36594

NASA's Space Research and Technology Program

Report of a Workshop



Aeronautics and Space Engineering Board
Commission on Engineering and Technical Systems
National Research Council

NASA's Space Research and Technology Program

Report of a Workshop

**Aeronautics and Space Engineering Board
Commission on Engineering and Technical Systems
National Research Council**

**NATIONAL ACADEMY PRESS
Washington, D.C. 1983**

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This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

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This report and the study on which it is based were supported by Contract No. N.ASW-3455 between the National Aeronautics and Space Administration and the National Academy of Sciences.

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Frontispiece: Artist's rendition of TDRS-I, part of the tracking and data relay system designed to eliminate the extensive network of satellite tracking ground stations and periods when orbiting spacecraft lose contact with earth stations (top), LANDSAT-D, the fourth experimental satellite for monitoring and managing food, fiber, and water resources, mineral and petroleum explorations and land cover and land use mapping (left), and FLTSATCOM-B, the spaceborne portion of the worldwide Department of Defense system enabling communications between aircraft, ships, submarines, and ground stations, Strategic Air Command elements and presidential command networks (right).

June 30, 1983

Dr. A. Richard Seebass, Chairman
Aeronautics and Space Engineering Board
National Research Council
Washington, D.C 20418

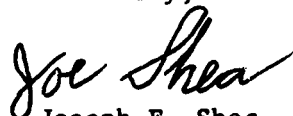
Dear Dr. Seebass:

I am pleased to transmit to you the report of the Workshop on NASA's Space Research and Technology Program. In keeping with the ASEB advisory responsibility to the Office of Aeronautics and Space Technology, this report represents the Board's first effort to address NASA's long-term role in space technology.

Representatives from the four major elements of the national space community participated in the workshop: commercial and civil users of space, the military, spacecraft and subsystems manufacturers and NASA itself. In examining the categories of technology advances of future potential importance to this community, the participants noted many areas overlapping among the four groups. This led to the conviction that an integrated advanced space research and technology program could indeed satisfy the needs of the broad national space community.

Perhaps, the most important outcome of the workshop was this consensus that OAST has a larger role to play in the development of space-related technologies than had been appreciated previously. For the past decade, the OAST program has been designed primarily to meet NASA's perceived in-house needs. Workshop participants agreed that basic work performed by OAST could provide the research results and technology innovation which the spacecraft and subsystems industries need to effectively respond to the commercial, civil and military users of space. Such activity often is not carried out by industry because it frequently involves high risk, large capital investment, and has a payoff far down the road. Thus, the workshop members strongly endorse the development of a closer NASA-industry relationship, analogous to the relationship that exists with the aeronautics industry--which has benefited not only NASA and industry but the nation as a whole.

Sincerely,



Joseph F. Shea
Workshop Chairman

WORKSHOP ON THE
SPACE RESEARCH AND TECHNOLOGY PROGRAM
of the
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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Executive Summary

The Office of Aeronautics and Space Technology (OAST) of the National Aeronautics and Space Administration is responsible for the advanced space research and technology development conducted by the agency. The Associate Administrator of OAST requested the Aeronautics and Space Engineering Board (ASEB) of the National Academy of Sciences/National Research Council to review the space research and technology program and to recommend what the future role should be in supporting not just NASA, but the national space community.

Two basic questions were posed:

- o Is the United States space community (the users of space, the spacecraft manufacturers, and the military) adequately served by the OAST space R&T program?
- o Should NASA/OAST have a role in space technology analogous to its role in aeronautics?

The charge was later expanded to include an assessment of technology requirements through the year 2000 and any recommendations for changes in OAST's program.

The ASEB empanelled senior representatives from private corporations, the military, U.S. government agencies that use space, major U.S. manufacturers of spacecraft and subsystems, and space engineering departments of major universities. The study participants examined the status of the spacecraft and subsystem industry (Chapter III) and the civil and military uses of space (Chapters IV and V). Generic and specific enabling technologies were identified.

It was found that U.S. spacecraft manufacturers support civil and commercial users, the military and NASA--and, in turn, are supported by subsystem suppliers. However, no single spacecraft program carries sufficient resources to develop advanced critical subsystem technologies and increasingly, U.S. suppliers are facing strong competition from foreign industry that is government subsidized.

The workshop participants concluded there was much OAST could do, that is not currently underway, to provide a stronger research base for users of space and the spacecraft and subsystem industry. The NASA role in spacecraft technology should be to stimulate subsystem technology advances and national expertise in all aspects of spacecraft technology. NASA is seen as potentially having a role in the development of space technologies that could provide important national benefits similar to those derived over the years from NASA's support of aeronautics research and technology.

Findings

- o Obvious high payoff uses of space have been identified and are maturing: communications and meteorology in the civil sector, reconnaissance, communications, meteorology and navigation in the military.
- o Potential benefits in other areas remain speculative. Earth resources, navigation in the civil sector, manufacturing in space, and advanced military missions have strong advocates but long term utility has yet to be demonstrated.
- o The high cost of space systems and transportation to space inhibits the civil and commercial use of space.
- o The space missions identified in this study exhibit a spectrum of common technology needs that could be served by an integrated national program.
- o OAST's current space technology program is primarily responsive to NASA's in-house needs, providing only incidental fallout to civil and military users and to the spacecraft industry. The space industry does not share the close working relationship with OAST that the aeronautics industry has enjoyed. NASA's role has been that of a customer, rather than a source for technology development.
- o It is just as true in the eighties as it was in the sixties that space can provide services of unique benefit to mankind; that space can provide new military capabilities that must be understood and mastered before it is done by potential adversaries; and that the high technology of space systems provides economic stimulation and technological fallout to society. Unique to the eighties is the foreign industrial competition which now challenges the preeminence of the United States in space technology. The United States, through NASA should continue to explore and stimulate potential uses of space as spelled out in the Space Act of 1958.

Recommendations

Upon concluding that NASA should make a long-term commitment to a

broad-based space research and technology development program that serves the national space community, the workshop participants developed the following recommendations.

Institutional Recommendations

1. NASA should establish the level of resources (funds, manpower, and facilities) to be allocated to advanced space research and technology development for the next decade and protect these resources from the short term requirements of NASA's major operational programs. The workshop participants believe the potential return, in terms of increased utility and lower cost of space operations, warrants strengthening and protecting the OAST space research and technology development program.
2. NASA should expand the charter of its space technology advisory committees, charging industry and university members with the responsibility of helping NASA to plan a technology program that is responsive to the needs of the broader space community and not just to NASA's in-house needs. At present, the function of these committees seems to be to review the program plans developed by NASA, which are largely directed to NASA's needs.
3. NASA/DoD cooperation should grow. The NASA/DoD Space Technology Interdependency Group has made good progress in defining the technical interaction between NASA and the Department of Defense. This effort to define the division of research and development responsibility in areas where interests overlap should continue, and the number of cooperative R&D programs should expand beyond the six already chosen to begin in 1984.
4. NASA should develop centers of technological excellence. NASA should develop centers of excellence where advanced research and technology development efforts in specific space disciplines would be concentrated and expert knowledge made available in a manner analogous to that in some aeronautical centers. Past experience with national laboratories shows that productive work comes from outstanding leadership, advanced facilities, a dedicated and skilled professional staff and institutional continuity.
5. NASA should provide access to space for experimental purposes as a natural extension of national aerospace facilities. NASA should promote an evolutionary program of on-orbit space experimentation involving zero-gravity, vacuum, and radiation effects. Such a program could culminate in a national space resource equivalent to the aerodynamic wind tunnels developed and operated by NASA.

Technical Recommendations

The workshop identified advances in critical technologies that would significantly increase performance and utility or lower the cost of applications of space. Although the priorities varied somewhat between the user areas, the commonality of both the technology needs and the quantitative goals desired was pronounced. The workshop concluded that NASA could readily develop a broad-based space R&T program that would serve a major fraction of the national space community and recommended that technology programs be vigorously pursued in the following areas:

1. Cost of using space

The high costs of manufacturing and testing spacecraft and their payloads, of transportation to orbit, and of space operations are the largest barrier to the use of space, especially by the commercial sector. This was regarded by all panels as the single highest priority and requires increased OAST emphasis. A significant portion of the OAST R&T program should be directed toward technologies that promise to reduce the cost of spacecraft subsystems, payloads, transportation and operation.

2. On-orbit propulsion

Development of on-orbit propulsion capability has been neglected over the last decade and in the workshop deliberations ranked second only to cost considerations in importance. NASA should revitalize a program to provide high specific impulse chemical stages for orbital transfer and station keeping to complement the Space Shuttle earth-to-orbit capability. Development of plasma propulsion systems which hold the promise of very high specific impulse should be pursued.

3. Technology enhancement for large space structures

Large space structures require long-term dimensional stability and resistance to distortion. Innovative design approaches and technological advances are needed to meet the challenges of construction, deployment, and maintenance of future space structures such as large antennas, large precision optics and platforms or stations. Key areas are: composition and erection of main structural elements, stiffness, thermal control and protection, heat pipe and coolant distribution improvements, lubricant development, inflatable structure application and simulation testing. NASA/OAST should develop the knowledge base for control of the geometry and orientation of large orbiting space structures.

4. Research on materials for space use

OAST should develop an appropriate data base for characterizing the performance of materials in the space environment, with particular attention to the long-term effects of temperature, out gassing, contamination, erosion, plasma effects, atmospheric density, and solar and nuclear radiation.

5. Architecture for organizing and disseminating data

A critical need exists to reduce time and costs required to obtain data from space in formats usable by the civil, commercial and military sectors. An efficient balance between on-board and ground-based processing must be determined, communication formats selected, and an approach to data archiving and retrieving established. Research in this area might be focused in a national earth resources dissemination facility that could demonstrate capability by servicing potential users.

6. Sensors/payloads technology

Rapid increases are foreseen in use of space-based sensors for detection, identification and tracking of earth, atmospheric, and space targets--using both optical and microwave techniques. The anticipated military requirements for electro-optical sensitivity and accuracy will lead to a need for very large, lightweight optics and mosaic focal planes of millions of detectors as well as very large radars. Sensors for commercial and scientific application payloads require improved spectral and spatial resolution and the ability to make self-determinations of when data should be taken. The workshop participants view the following areas as amenable to quantum jump improvements: microwave sensing (both passive and active), visual, infrared, laser, and particle sensors.

7. Communications technology

This area, while related to data processing and payload categories, is important enough to merit special mention. Military requirements for privacy and information content are moving carrier frequency selection to higher bands (possibly above 100 GHz) and bandwidth demands continue to increase. The same requirements drive improvements in antenna designs and figure maintenance. Earth resource and environmental needs include low noise receivers, high-power linear amplifiers, signal processors, and more efficient and intelligent data-compression techniques. Commercial applications press for antennas that are large and agile.

8. Power systems technology

Spacecraft power systems include power generation, regulation, distribution and energy storage. By the year 2000, civil needs will be four-to-five-fold present requirements and DoD needs will be approaching a megawatt. Peak-to-average power ratios for missions such as space radar will be as high as 20:1. Longer life and reduced weight, along with energy storage, will be the driving needs. Development is essential in batteries, solar arrays and solar cells, nuclear power systems, and high voltage distribution.

9. Environmental control

Pollution in space is a serious problem. Effort is required to reduce contamination of optical and other sensors and environmental monitors from propellant effluents, material out gassing, and particulates carried within the cargo bay. The radiation environment also poses problems of spacecraft charging and degradation of microelectronic components which must be addressed.

10. Thermal control

Spacecraft trends toward longer life, higher heat loads and fluxes, stored cryogenic propellants, increased use of infrared sensors, closer dimensional control, radiation and laser vulnerability, and the future involvement of man in operations and refurbishment contribute to new requirements for thermal control. Analytical processes are needed to define and evaluate thermal control designs. New concepts and devices will include advances in low temperature heat pipes, two-phase thermal management systems (pump assisted heat pipe or vapor chamber); lightweight flexible fluid lines with zero leak disconnect capability; long life, low temperature refrigerators; lightweight radiators; high-flux laser mirror cooling and cryogenic propellant storage and transfer systems.

11. Navigation, guidance and control

The need for accurate autonomous navigation and attitude and figure control for large flexible structures will require developments in the technology for satellite stability, pointing, maneuvering, attitude determination and control, navigation, and the devices needed to provide these functions for future spacecraft.

12. Support of man in space

The capabilities to repair, maintain and construct orbiting space hardware will require improved life support systems and

flexible space suits with rapid ingress/egress to permit man to leave the shuttle and work effectively. Small, responsive space transportation systems with micro-level thrusters will be required, along with manual and "tele-" tools. An understanding of and remedy for motion or space sickness and other physiological disorders are also needed.

13. Survivability

Autonomy and radiation hardening are the principal issues. Most current spacecraft afford some protection in the event of an on-board electronic failure or loss of ground control; the most commonly used technique is an automatic maneuver into "safe-hold" and a shut-down of non-essential functions to conserve power. Sophisticated spacecraft computers, comparable to today's super computers, along with the application of artificial intelligence techniques could lead to highly autonomous spacecraft capable of diagnosing and correcting on-board failures and of performing long missions in space independent of control from the ground. Radiation hardening of spacecraft is mandatory for military space systems, but civilian spacecraft will benefit from the technology because they would be more resistant to failure caused by natural radiation.

I.

Introduction

For several decades, the space research and development projects of the National Aeronautics and Space Administration have provided dramatic scientific and technological breakthroughs enabling the United States to lead in the exploration of the solar system, in the various disciplines of space science, in revolutionary communications advances, and in earth observations from space. The success of NASA's space and aeronautics programs can be attributed to the excellence of its research laboratories, active relationships with university researchers, and a productive partnership with private industry.

The NASA space technology program consists of work conducted under contract by industry or universities, through grants to universities, or in-house at the NASA centers. This work is sponsored by several NASA program offices, namely, the Office of Space Tracking and Data Systems, the Office of Space Flight, the Office of Space Science and Applications, and the Office of Aeronautics and Space Technology. Each of the NASA program offices except the Office of Aeronautics and Space Technology (OAST) is mission-oriented, and the research and technology development effort supported by these offices is focused toward satisfying mission objectives and tends to be focused on near-term and systems-oriented investigations.

The space research and technology development (R&T) sponsored by OAST serves dual purposes: OAST activities are coordinated with the other program offices and its R&T supports the mission needs of those offices. For example, OAST programs frequently apply directly to planetary and space science missions; e.g., technology developed by OAST on reentry aerothermodynamics and on materials will be used for Galileo's planetary entry. At the same time, OAST activities represent NASA's commitment to advanced, non-mission-specific research and technology intended to provide the advanced technology base that the other program offices, the Department of Defense, and manufacturers of space systems will use for new projects in the future.

It is generally recognized that OAST provides appropriate support to NASA program offices; however, it is not clear that OAST's effort

is adequate to provide the advanced technology base that will be required in the future to meet the needs of the manufacturers of spacecraft and subsystems for civil and commercial uses of space and the military.

In September 1981, the NASA Associate Administrator for Aeronautics and Space Technology discussed with the National Research Council's Aeronautics and Space Engineering Board (ASEB) his concern as to whether OAST was responsive to the future technology needs of the civil, commercial, and military users of space and whether NASA should play a role in space technology analogous to its support of U.S. aeronautics. An ad hoc ASEB panel was formed and, working in cooperation with OAST, in December 1981 reported that the OAST program appeared to be dependent on other NASA organizational units, specifically the Office of Space Science and Applications, for perception of the needs of users, whether governmental, academic, or industrial; that while industry interaction is encouraged through various working groups, OAST and industry were not well coupled; and that the Associate Administrator's concerns were well founded.

ASEB was then requested to convene a summer workshop of appropriate representatives from the spacecraft industry, the space user industries, universities, the Department of Defense, and NASA to identify technology requirements through the year 2000 and to recommend any changes in OAST's program that would better align it to meet the future technology needs of users of space and the spacecraft industry.

II.

Approach

Planning for the NASA space research and technology workshop culminated in the spring of 1982 with the formation of study panels on (1) the commercial uses of space, (2) spacecraft manufacturers' requirements, and (3) future technology needs. In addition, two smaller groups were formed to consider the NASA/industry interface and NASA/military areas of interdependency. The chairmen of the above groups composed the steering committee for the workshop.

The initial meeting of the steering committee on April 26, 1982, included discussions with NASA representatives concerning the rationale and expectations for the workshop as well as appropriate briefings. Participants for the panels were identified, and it was agreed to solicit information from key space industries and government agencies regarding future space R&T needs.

In early May 1982, information about the workshop was sent to 29 companies representing users of space in the fields of communications, earth observations, climate and weather, navigation, and materials processing and to 14 space systems manufacturers. On July 15, a similar letter was sent to 34 space component and device manufacturers. Questions were posed to them on the following:

- o Their views regarding the principal commercial space products and services through the year 2000
- o Specific technological advances needed to enhance or expedite the commercial use of space
- o Potential new markets that might be available with the development of new technologies
- o Areas of technology that might offer increased performance, capability, availability, or efficiency in space systems

- o Ways NASA can best support the commercial space industry and manufacturers of military space systems and recommendations for possible programs
- o Enhancement of the transfer of the results of NASA's space R&T program to the private sector

Responses from both groups helped to target major areas of concern and contributed substantially to the workshop's data base. A listing of respondents is included in Appendix E.

On June 29, 1982, members of all panels met in Washington and were briefed on OAST's current program and long-range plan for space R&T; the NASA Space Systems Technology Model; the Military Space Systems Technology Model; NASA's communications programs; and military R&T needs. On June 30, the individual panels met separately, identified issues and questions, determined the need for additional information, and assigned tasks to members. Using the results of these preworkshop meetings, the outline of the workshop report was prepared.

The workshop was held August 30-September 3, 1982, at Woods Hole Study Center. Reference material is listed in Appendix E. On the first day, participants were addressed by Robert S. Cooper, Director of the Defense Advanced Research Projects Agency, Jack L. Kerrebrock, NASA Associate Administrator for OAST, and Burton L. Edelson, NASA Associate Administrator for Space Science and Applications, and were briefed by John W. Townsend, Jr., on the findings of a National Research Council Space Applications Board study held August 15-21, 1982, on practical applications of space systems and their implications for design of space stations and space platforms. The chairmen of the panels summarized preliminary efforts in plenary session and during the week each panel developed its conclusions, recommendations, and supporting arguments. On one afternoon ad hoc discussion groups met and further explored the issues of NASA/industry, NASA/academe, and NASA/military relationships as well as NASA's role in helping industry to meet foreign competition. The conclusions reached by each group are embodied in the report.

The drafts prepared at the workshop were subsequently condensed, edited, and merged together by members of the steering committee and the staff. There was a question of how completely the findings should be integrated and, at the risk of a degree of redundancy, it was agreed to preserve the integrity of the work of the major panels (users of space--civil and military, spacecraft and subsystem manufacturers, and specialists in space technologies) and to emphasize that these groups had arrived at similar conclusions working independently.

The workshop results were subsequently reviewed by the Aeronautics and Space Engineering Board.

III.

A View of the U.S. Space Community

An assessment of NASA's future in space technology must take cognizance of the current and projected status of the United States in the use of space and the manufacture of spacecraft. At the same time, it is useful to observe the difference in NASA's role vis-a-vis the aeronautics industry and its past relationships with the U.S. space community.

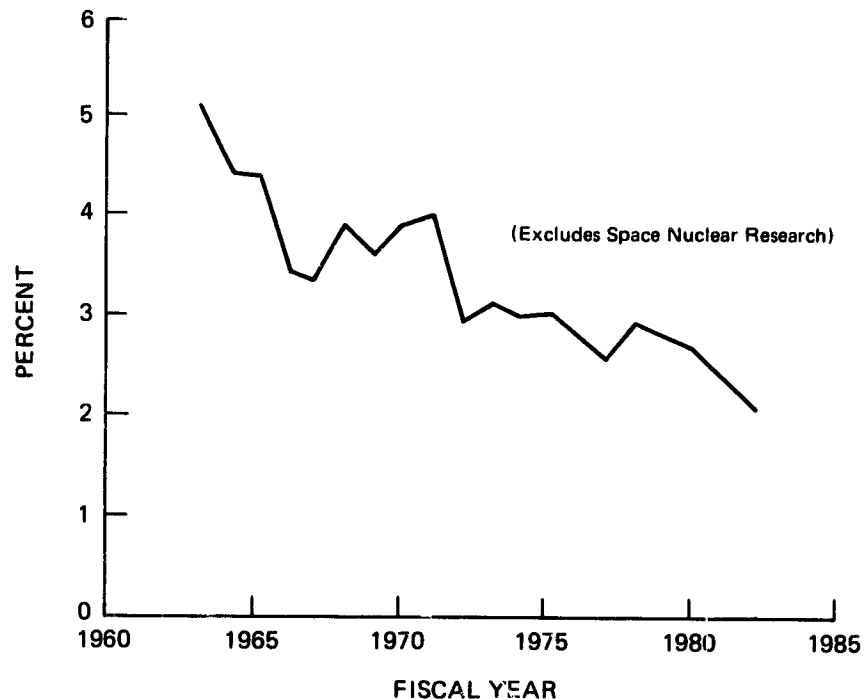
Entering the Space Age

The United States entered the space age in 1958 with the launch of Explorer 1 on January 31 and the passage of the National Aeronautics and Space Act on July 29, which restructured the National Advisory Committee for Aeronautics (NACA) to form the National Aeronautics and Space Administration. NACA had guided and supervised research and development of technology for military and civil aeronautics in this country. Where NACA's strength had been in aeronautical research and technology development, the new space agency focused on manned space flight and on launching and operating research payloads. Space research and technology development within NASA supported space exploration and culminated in the manned missions for which the U.S. has become famous--Mercury, Gemini, and Apollo. At the same time, a strong space applications program was developing in the areas of communications, earth sensing, and meteorology.

In the development of satellites, the early successful launches of 1958-59 were followed by explosive growth in the 1960s. By the end of the decade, NASA had successfully launched over 150 payloads including nine Intelsat commercial communications satellites. Satellite communications had become the principal means of global telecommunications. Similarly, the first meteorological satellite, TIROS 1, was launched in 1960 and weather satellites came into full operational use during that decade. In 1972, the first earth resource satellite, LANDSAT 1, went into orbit. Almost all of the technology used in these communications, weather, and earth resources satellites was developed by NASA, either in-house or by its industry or university contractors.

Significant Changes

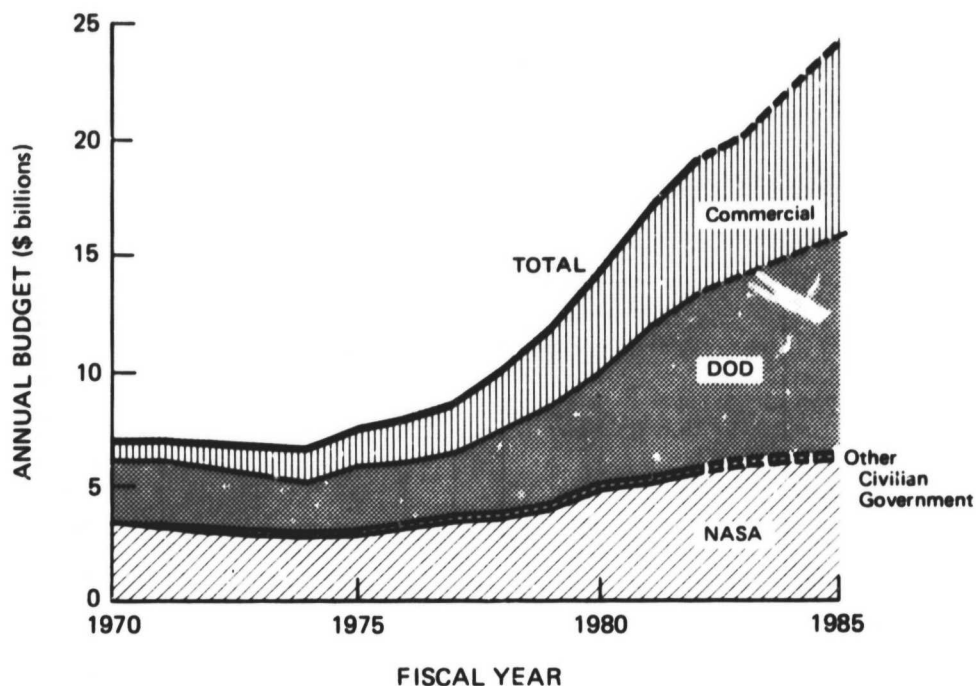
In 1973, NASA funding for development of advanced communication satellite technology was terminated, the justification being that this work should be assumed by commercial organizations. Despite the spectacular successes of the earlier years and the well-known benefits of the spinoffs from space technology, the commitment to research for the long term has fluctuated dramatically. With unprecedented inflation and shifting national priorities, the temptation in many segments of the economy has been to defer fundamental research in order to cope with immediate needs, and similarly, as space shuttle development costs escalated, NASA support for basic space research and applications declined. In fiscal year 1962 NASA's R&D budget for space R&T represented 5 percent of the overall NASA budget; in fiscal year 1982 it was close to 2 percent (Figure 1).



SOURCE: NASA/OAST

FIGURE 1 Space R&T as Percent of NASA's R&D Budget

The emphasis of U.S. use of space gradually changed as well. For the first time, the 1982 national space policy became a classified document and funding for defense space programs exceeded the NASA budget. Figure 2 shows this shifting balance of support for space R&T and indicates an expanding DoD and commercial space effort.



SOURCE: NASA/OAST

FIGURE 2 National Space Effort

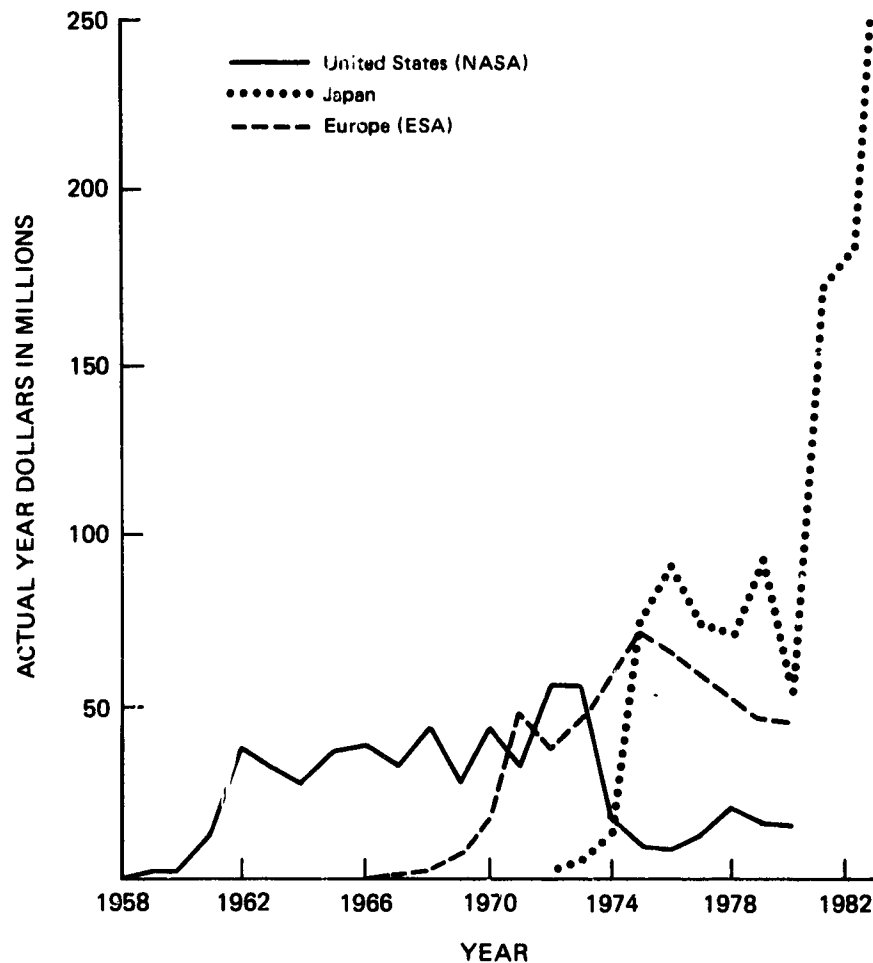
In this changing climate, the industrialized allies of the United States have clearly not been idle. Figure 3 illustrates the dramatic entry of the Japanese and Europeans into the space arena. A survey of launch capabilities shows similar growth abroad as well. (Appendix A reviews in detail the development of U.S. and foreign satellite system technology from 1958 to the present.)

NASA's Research Role

In the field of aeronautics, NASA has historically provided a central technological resource that U.S. aircraft companies have drawn upon. NASA and its predecessor, NACA, worked effectively and in harmony with the aeronautical communities for two-thirds of a century, with resultant strength in U.S. aeronautics.

As discussed above, NASA's space R&T has been tailored to the technology requirements of NASA missions. The following chapters explore the desirability for the NASA Office of Aeronautics and Space Technology (OAST) to conduct the research and provide the technology that will permit the U.S. industry to exploit the use of space for civil and military uses.

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SOURCE: NASA

FIGURE 3 Budgets for Communications Satellites
(Government Sponsored R&D)

U.S. government policy as expressed in Special Analysis K, prepared by the Office of Management and Budget in 1982, states "... R&D activities are supported by the federal government in two broad categories, namely, to meet:

- o Federal Government needs--where the sole or primary user of the R&D is the Government itself, for example, in national defense and environmental regulation.
- o National needs--where the Federal Government helps to assure the strength of the Nation's economy and the welfare of its citizens through the support of R&D in specific areas such as agriculture, energy, and health."

It continues, "... the Government should focus its direct R&D support on those areas where there is substantial prospect for significant economic gain to the Nation, but where the private sector is unlikely to invest adequately in the national interest because the benefits, in large measure, are not immediately 'appropriable' by individual firms. Thus, for example, the Federal Government supports basic research across all scientific disciplines but limits its spending on technology development to technologies requiring a long period of initial development, such as fusion power, where the risk is high but the payoff to the Nation is potentially large."

Certainly, the U.S. government is frequently the primary or sole user of a space application, many of which provide essential public services. Military and commercial technology are often interdependent and indistinguishable as will be discussed in following chapters.

Most significantly, past experience shows that much basic research simply will not be performed by industry. Space technologies often require many years of initial development, and in these cases there is little likelihood the private sector will invest adequately due to the high risks involved relative to the capital outlay required and to the long time required for return on investment. With high costs of investment funding, industry is reluctant to embark upon the research needed for major breakthroughs that will probably not occur for many years in the future. Indeed, the sums required to introduce major innovations may exceed the net worth of a manufacturer. In the early 1970s, NASA's research program for advanced communications satellites was stopped on the grounds that such work could be supported by Intelsat. However, a recent experimental communications satellite (the ATS-6, launched in 1974) cost approximately \$200 million, while Intelsat's gross revenue in 1974 was \$101 million.*

Space research and development is unique in that quantities of most systems are small and the risk to the manufacturer may be great. However, many of the key subsystems could have common application to a number of systems. Thus, NASA support at this subsystem level could offer broad research support to industry users.

* Metzger, S., Overview of Satellite System Technology, Appendix A

In the 1958 Space Act, one goal of NASA was seen as "... preservation of the role of the United States as a leader in aeronautical and space science and technology and in the application thereof to the conduct of peaceful activities within and outside the atmosphere." In the present climate of stiff international competition with foreign space industries often government owned or heavily subsidized, basic research and innovation will be central to the U.S. use of space and to the health of both government programs and the commercial industry.

IV.

Future Civil and Commercial Uses of Space

The Civil User Panel projected the use of space for practical purposes through at least the end of the century. The panel then identified the key areas that would benefit from research and technology development in such a way as to lead towards accelerated applications of space, as well as those that might inhibit full growth.

The following uses are described below in order of the expected extent of use by the year 2000:

- o Communications

- Fixed Service

- International Satellite Communications
 - Domestic Satellite Communications

- Direct Broadcast Satellite Communications

- Land and Sea Mobile Satellite Communications

- o Navigation by Satellite

- o Meteorology

- Short-term Events/Weather

- Long-term Events/Global Environmental Quality

- o Remote Sensing

- Land Remote Sensing--Renewable Resources

- Land Remote Sensing--Non-Renewable Resources

- Ocean Research and Services

- o Materials Processing

It is clear that the use of space for communication purposes will dominate all other uses in the foreseeable future. Commercial uses are discussed in this Section; military communications needs are treated in Chapter V. Other users may be civil government, or, in the case of materials processing, industrial. The word "user" in this section seldom means the ultimate end user who might be a farmer, a geologist, a business owner, or the general public, but rather the system operator who provides a service to his customers. This distinction makes little or no difference when one considers research and technology development programs (except for distribution and dissemination techniques), but will have a bearing on who operates such systems and how they are paid for. Regardless, advanced technology in key areas will promote the practical use of space.

Communications

Fixed Service

Fixed service provides point-to-point and point-to-multipoint communications of voice, data, video, and graphics. This service is well established and growing rapidly both in the quantity of communications provided and in the diversity of services offered, and employs a mature technology. Present international telecommunications satellites (Intelsats) involve approximately 1000-kilogram satellites placed in geosynchronous orbit, and 2000-kilogram satellites are being produced for launch in 1986. Most present domestic satellites (DOMSATS) involve approximately 540-640-kilogram satellites. Full eclipse capability and full stationkeeping capability are necessary. A typical spacecraft will perform its function in space for more than seven years. The transponder arrangements are Frequency Division Multiple Access (FDMA) with typical center-to-center spacings of 40 megahertz. Present-day designs typically provide 24 such transponders, 12 coupled to a vertically polarized antenna and 12, interleaved in frequency, coupled to a horizontally polarized antenna. Multiple transponders satisfy requirements for diverse services. A typical DOMSAT operation permits trunking between major earth stations and provides services such as single-carrier FM TV. Flexibility of operation is of paramount importance.

International Satellite Communications

International communications is expected to continue its strong growth through the end of the century, with a total of 750,000 international satellite voice communication channels being in use by the year 2000. New international submarine cables using light waves will also be in place, carrying 20 to 30 thousand voice circuits in the Atlantic Basin alone. Both satellites and light pipes are generally placed in service with sufficient excess capacity to handle reasonable service growth. However, satellites also have provided additional capacity over periods of several weeks to restore service during outages due to cable breaks. Satellite outages are less common; spare backup

capacity is provided by a completely separate satellite, keeping net outages to the order of minutes. Satellite and light pipe cables will become more complementary toward the year 2000, with the division of traffic made on the basis of efficacy and cost. The traditional large gateway earth station carrying many thousands of communication circuits will be supplemented by many smaller, special purpose earth stations located at points of traffic concentration. These may be multiple-user, or single-user terminals, depending on traffic. New integrated voice/image/data services will be in common use, primarily for business purposes, although voice traffic will still predominate. The international communication system will continue to provide interface transparency between new and complex services, such as Integrated Services Digital Networks (ISDNs) that function with different local standards. Video teleconferencing will be one of the major international wideband services. Full motion, studio-quality color video will be used for teleconferencing, utilizing compression techniques that will reduce bandwidth requirements by a factor of ten. Although many services will utilize digital techniques, end to end, other services, particularly small traffic streams, will use new bandwidth efficient analog techniques. International maritime services will be in widespread use by a broad spectrum of watercraft throughout the world. Very narrow band toll-quality voice and data communications will be predominant, but hazard and weather communications will also be routine. Late in this century, low-cost precision navigation services will also be delivered.

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Domestic Satellite Communications

Domestic satellite networks will tend to be specialized rather than multiple purpose. Each specialized segment will grow at a rate peculiar to its own market, with major dependence on the quality and costs of the services. These networks will have terrestrial competition, in most cases, to a much greater degree than do international systems. The greatest use will be for studio-quality entertainment television, closely followed by voice communications via public message service or private line networks. Direct-to-home television broadcasting will be another use, followed by integrated and specialized digital voice/data/image services, including video teleconferencing. The challenge to technology will lie in driving the costs of these services low enough so that a broad marketplace will be served. Communications by satellite will be the common and accepted mode for business communications, while developments in source and channel coding will result in very efficient use of the radio frequency spectrum. Hence, even though the business use of satellites will be extensive, it will require much less of the available bandwidth than the other services. Full motion, studio-quality video teleconferencing will be used to the extent that many traditional business practices will disappear. Businesses will reach directly into the home at all hours, reducing the conflict with other activities and obviating the need for much travel. Many public services will be offered via domestic networks, including paging, medical assistance, fire and break-in alerting, severe weather

warnings, and perhaps even voting. Newspapers and magazines will transmit composed, press-ready, full color text and photo materials for local reproduction and distribution. Despite present institutional and national policy considerations, the future extension of many domestic services to international destinations will be well under way.

The earth station subsystems and components for domestic satellite communications systems are mature, produced in significant quantities and are competitively priced; however, the complexity of the larger trunking stations, the relatively few-of-a-kind that are produced, and future use of satellites with scanning spot beams should permit smaller, less expensive earth stations for certain applications.

Fixed Service Technology Implications

Aside from obvious improvements in low-noise amplifiers and power amplifiers and replacement of tube amplifiers by solid state amplifiers for higher reliability and reduced weight, the principal future technical problems are concerned with the use of spot beams and the solution to the resultant beam interconnectivity problem. While the antenna technology is relatively mature, the formation of flexible arrays of spot beams, possibly with steering, and with good polarization purity and low side lobes, is an unusual challenge to antenna engineers. In addition to implementation of offset parabolic sections with multiple feedhorns, increasing attention should be given to phased arrays and to scanning antennas. Phased arrays are attractive because of the ability to imbed small, high-performance active elements in the antenna elements to achieve the steerability and illumination control inherent in these antennas. Narrow spot beams, each illuminating a small fraction of the total service area, but steerable to permit coverage of any desired part of the area, are expected to be used. Both of these antenna types offer the possibility of narrow spot beams, only where they are needed. More conventional multiple, fixed spot beams also will find widespread use. These complex satellites require advanced on-board processing to accomplish the interbeam routing. The simplest implementation is satellite switched time division multiple access (SS-TDMA) using nanosecond speed switches composed of diodes or transistors.

Future systems will require larger switches (more antenna beams), faster switching speeds, and wider bandwidths. Frequency division multiple access (FDMA) routing involves extensive on-board filtering to provide interbeam "paths" (routing of individual signals is not necessary). Because of the inherent inflexibility of the method, "slow" switching is usually included in order to be able to change the routing patterns. Lightweight channelization is the key to a weight-efficient design. FDMA is attractive because it imposes the least burden on the earth station performance and, hence, results in the lowest cost earth station--particularly attractive for customer premises services. The third method, on-board processing, while the most challenging, also offers great potential. An on-board processor

provides demodulation, buffering, switching, reformatting, and modulation. Thus, a bit stream can be regenerated on the satellite, making the uplink and downlink bit errors independent, thus improving the performance of these links. In addition, modulation can be changed, access method can be changed, and interbeam switching provided. Packet switching also is possible whereby the beam destination can be imbedded in the bit stream, thus relieving the earth station of the obligation (and cost) of synchronizing the burst.

The processor envisioned for these tasks is a complex array of high-speed digital assemblies with automatic fault detection and redundancy. Such systems can be very complex, but early implementations will be relatively simple and can also provide ancillary computational services for attitude control, tracking, telemetry command, and so on.

The success of private, corporate, and government networks will eventually increase the demand for greater interconnectivity. This problem is already a major one for Intelsat, because, although major earth stations have two or more antennas, most have single antennas and only one satellite can provide interconnectivity among them. In this environment, it is not effective to increase capacity by adding more satellites. Single-satellite capacity is limited by launch vehicles, spectrum allocations, and the huge investment in existing earth stations. One solution is intersatellite links (ISL). These should find application first in Intelsat and later in domestic systems.

Direct Broadcast Satellite Communications

By the year 2000, direct broadcast satellites (DBS) will be delivering a variety of services to homes and business. Although entertainment will be the predominate use, specialized business and public services will be common. Many of these services will be aimed at markets not served, or inadequately served by cable or other conventional means. Extensive work on lowering costs and expanding the spectrum of services will be nearing completion, permitting DBS to begin displacing capital-intensive cable TV. High Definition Television (HDTV) will be overlaid on the pioneering DBS services and gradually displace standard TV, much as color TV displaced black and white. Both standard TV and HDTV will be simulcast, removing the need for viewers to choose between broadcast standards.

Direct Broadcast Satellite Technology Implications

The heart of a DBS satellite is the high-power Traveling Wave Tube (TWT) and its high-voltage power supply. Lightweight helix TWT's with matrix cathodes and multiple collectors are presently being procured; however, considerable experience with this technology will be needed to assure long life. There seems to be no practical solid state alternative to the TWT for the near future (because of the high efficiency needed). Manufacturers will be content if these tubes are

long lived, as predicted, and can be delivered to reasonable schedules. Some small improvements in traveling wave tube weight and efficiency is to be expected. Antenna technology for shaped beam antennas of high efficiency is at hand although future improvements can be expected. These characteristics, based on offset fed parabolic sections, are used to achieve adequate sidelobe and cross-polarization performance. A reliable, lightweight deployable aperture could save significant payload weight. The remaining transponder parts are of little consequence to improved system performance.

Technology areas important to the users of space for both fixed service and direct broadcast are those that significantly influence the cost of delivery of the service. Key spacecraft technologies are those that make efficient use of bandwidth and those that reduce power, mass, and housekeeping requirements. Earth segment technologies of importance are those that reduce physical size of antennas and facilities, reduce prime power requirements, and enhance the reliability of both baseband and radio frequency equipment. In special cases, cost is fundamental to success. A data collection terminal should cost about \$1000, a personal communication terminal \$100.

Land and Sea Mobile Satellite Communications

These systems are concerned with communications to mobile and special portable terminals and involve all of the generic communications services, including voice, data, text, position fixing and facsimile, and possibly some low bandwidth video. There is no U.S. land mobile satellite system. Activity is confined to technology development, system studies, and marketing assessments. Aero mobile systems do not exist and none are planned. There is a maritime mobile system under the stewardship of the international maritime satellite consortium with approximately 1500 ships now using satellite communications operationally.

Land mobile services can be provided to nonmetropolitan areas, suburban and rural, that are not served by terrestrial mobile radio telephone service, throughout North America and worldwide. Charges will be comparable to that of the conventional mobile radio service. Radio phone, dispatch, and data channels will be available.

The most likely application appears today to be the completion of mobile telephone networks by providing links to thinly populated areas where the satellite may offer a cost-effective alternative to the terrestrial networks. Reliable and rapid communications could be provided within a wide geographical area where such communication is limited or does not exist.

Other user applications include public safety, emergency medical care, energy management, disaster relief, and search and rescue.

In the case of sea mobile services, requirements from the user

standpoint include automatic calling, medium and high-speed data transmission, and other modern telecommunication services available on land. Connection to national and international networks and thence to telephone and telex exchangers for telephone, facsimile, low-speed data, high-speed data, telex, and possibly video are all desirable.

Mobile Service Technology Implications

The technology to enable the placement of a large deployable antenna with multiple spot beam capability at geosynchronous altitude is a key requirement for future mobile service communications. Antenna isolation between co-channel beams also is an important parameter. On-board FDMA switching may be needed eventually to provide mobile-mobile communications or to provide interbeam signal routing if the fixed link also uses multiple beams. Because of the small frequency bands allocated, spectrum efficient modulation is also important for high capacity. Modulations such as amplitude companded (compressed and expanded) Single Sideband-Amplitude Modulated (SSB-AM) and linear predictive encoding are especially attractive. Efficient linearized solid state satellite amplifiers also are needed. Mobile satellites operate in regions of the spectrum that are not now currently active so that there is a dearth of information about equipment and device characteristics.

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Navigation by Satellite

Mobile communications and navigation are closely interrelated. The increasing cost of fuel forces mobile vehicles on land, sea, or in the air to search for the most economical and safest course or flight path. The advent of the use of satellites for navigation has made it possible to satisfy these requirements within attractive economic limits.

Civil uses of navigation aids exist in the following categories:

- o Spacecraft launch operations, orbit determination, re-entry navigation, and landing operations
- o Airborne intercontinental enroute navigation, domestic enroute navigation, and remote area navigation
- o Search and rescue vehicle safety, position reporting/monitoring, rendezvous operations, coordinated search operations, collision/hazard avoidance, and monitoring and tracking hazardous cargoes on land or sea
- o Maritime ocean navigation, harbor operations, and coastal navigation
- o Land-based vehicle monitoring, schedule improvement, and optimal routing

- o Static positioning/timing, resource exploration, hydrographic surveying, aids to navigation positioning, time transfer, and geophysical surveying

As the navigation satellite system gains acceptance by the civil community, more sophisticated uses for such systems will emerge.

Meteorology

Environmental remote sensing ranges from monitoring short-term events (such as severe storm episodes or the eruption of a volcano) to evaluating long-term changes (as in the case of slow changes in trace atmospheric constituents).

Short-Term Events/Weather

The need to capture the short-term type of event dominates the remote sensing requirements for meteorological purposes. Meteorological measurements are required to meet the needs of the local severe storms forecaster--whose time scales may run from minutes to a few hours at most--or the analyst preparing a medium-range forecast for the next 3 to 10 days. The former requires greatly condensed data in a form that facilitates rapid, interactive manipulation by the forecaster. The man-machine interface becomes vital, as does the speed and ease with which data sets can be accessed, reformatted, tailored, and displayed. Although automation will be universal, it will exist to serve the needs of an individual who will apply knowledge and judgment of the local peculiarities of weather patterns and events to produce public alerts and warnings. These requirements lead to the need for systems that provide a frequent or even near-continuous monitoring function. This in turn leads to the current complement of polar-orbiting and geostationary meteorological satellites.

At the other extreme, the medium-range forecaster must have automated means to assimilate huge data sets from terrestrial, radiosonde, and satellite networks into massive computer models. Here the emphasis rests on validating and assembling data into formats that best fit the physics of the problem and the model employed by the computer--followed by rapid analysis of the data using high-speed computers.

Three separate trends will dominate user requirements over the next two decades; they relate to sensing instrumentation, computation and correlation, and communication.

In sensing, the requirements for sensor evolution will include a continued subdividing of sensor wavelength bands, extensions into new spectral regions (particularly microwaves), and enhanced spatial resolution.

In the area of computation and correlation, the trends toward correlative analyses of multiple data sets found in widely varying formats will continue and become more and more vital.

In communications, the ease, rapidity, and cost with which data can move over international distances, from source to user, or from data base to user will determine whether continued evolution of the weather forecasting capabilities will occur. Data from ships, aircraft, remote data collection platforms, radiosondes, people, and satellites must be transmitted from source to user with time delays that are consistent with the variability of the meteorological situation.

Looking to the next decade or two, the above trends will evidence themselves in a number of very specific areas, including:

- o Near-continuous, high-resolution, infrared sounding and multispectral imaging capabilities for the geostationary weather satellites
- o Improved microwave sounding and multi-spectral imaging capabilities for the polar-orbiting weather satellites
- o Lightning monitors on the geostationary weather satellites
- o Stereo imaging on a routine basis from the geostationary weather satellites for monitoring storm intensity, growth, and multilevel winds
- o Interactive computers at national centers and field units for improved use of satellite data and other information

Over a somewhat longer period, the trends will lead to:

- o Multiuse, multiwavelength sensors with accompanying data-processing devices to produce simultaneously products for a wide variety of applications
- o The capability to carry out microwave soundings from geostationary orbit--on the assumption that large aperture antenna technology will continue to evolve in other programs

Clearly the most essential ingredient in all of the above is to achieve this evolution of new capabilities and technology at an affordable cost. In particular, the cost must be commensurate with the anticipated value of the capability.

Long-Term Events/Environmental Quality

As noted above, environmental remote sensing ranges over time scales from minutes to decades or centuries. Atmospheric pollution events

tend to be short-term, as do estuarine, coastal, or ocean pollution events. Monitoring such events requires a continuous sensing capability--even though special measurements are made on a "call-up" basis; therefore, the continuous monitoring requirement is similar to that needed for short-term purposes. For these reasons, the user requirements and technological trends discussed previously under short-term events/weather apply to short-term pollution events, and that discussion will not be repeated here.

A major difference occurs, however, when very long-term environmental changes are to be evaluated. Such changes necessitate the precise measurement of exceedingly small variations and often permit monitoring at infrequent intervals--as opposed to continuous, repetitive monitoring. Under such circumstances, the maintenance of accurate calibration and the ability to cross-check measurements through alternative techniques become drivers for the evolution of both applications and technology.

The most pressing needs involve assessing climatic variables that may produce changes in either local or global temperatures or the measurement of subtle changes in the constituents of the atmosphere (trace species in the troposphere or stratosphere or stratospheric aerosols). These needs relate to the highly publicized discussions concerning air quality, depletion of the ozone layer, and the production of acid rain.

Current R&D activities are directed to developing instrumentation for making measurements of stratospheric trace species. This work is to be complemented by on-going activities in laser heterodyne spectroscopy and specialized space shuttle instruments that will be flown in the 1980s. The instrumentation tends to be exotic and fragile, but is well suited to use in a reflyable mode. The frequent use of solid cryogenics is likewise suited to short-duration missions, particularly when the detector requires temperatures well below that of liquid nitrogen. A major source of controversy in such measurements lies in data interpretation and the reconciliation of measurements made at different times by different instruments--yet this latter step will be essential to establishing the credibility of the result.

Remote Sensing

Land Remote Sensing--Renewable Resources

Different types of activities relating to renewable resources can be served by space-based remote sensing techniques. Because of the many different potential applications, the degree of spatial resolution needed varies as does the timeliness of data, geographic coverage, and other factors.

The following is a listing of examples of the use of space for the management of renewable resources:

- o Long-range forest and land use inventories and soils mapping
- o Short-range inventories (irrigated versus nonirrigated cropland, area estimates of specific crops or crop types such as small grains)
- o Crop yield estimation
- o Water resource management
- o Early detection and evaluation of stress conditions (moisture, disease, winter kill, pollution, other man caused stresses)
- o Evaluation of extent and severity of damage from natural disasters (floods, forest fires, volcano eruptions)
- o Soil moisture and other hydrologic modeling information

The application of remote sensing to each of the above has been investigated and some successes have been demonstrated using satellite data that is available.

A major limiting factor to remote sensing by satellite has been the uncertainty about the continued availability of timely, high-quality data. In fact, the case might be supported that continuity of data is the most important single factor in the practical use of satellites by the producers of renewable resources. These users of satellite data have shown great resourcefulness in adapting available data to their information needs. An example of the adaptation to existing data sources is the utilization of data from the NOAA 6 weather satellite with its very coarse resolution instead of LANDSAT data for monitoring conditions in foreign countries because the NOAA 6 data is available on a shorter repeat cycle and is more timely. The NOAA 6 data cannot provide as much information for a particular date as comparable LANDSAT data, but the availability of the data outweighs the quality of data for the present mode of operation.

If continuity and timely delivery of data to the users is the single most important factor, cost considerations are not far behind. The data collection system must provide affordable data in order for renewable resource users to make substantial commitments and investment.

Land Remote Sensing--Non-Renewable Resources

Exploration for non-renewable resources on earth from space is different from other major application areas; space sensors are never the primary source of data that are critical to solving exploration problems. Because of this, the non-renewable resources industries, e.g., the oil industry, measure the economic value of space

applications in a manner often very "foreign" to other users of space (such as the communications industry and meteorologists). The non-renewable resource industry must spend very large amounts of capital before even knowing a "find" is economically viable let alone realizing any cash flow from production of the resource. Because of the capital outlay that is normally required up front, the industry willingly invests large dollar amounts to minimize the risk of investing in a "find." In other words, if data from a satellite can decrease the risk even 1 percent on a \$1 billion program then expenditures to at least \$10 million can be justified.

Depending on the resource, surface indicators that add information to the evaluation of a given area include:

- o Gases in the air immediately above or in the surface material. Examples are radon (uranium deposits) and methane (petroleum deposits)
- o Vegetation modifications, for example, vegetative stress from high concentrations of metals in the soil (nickel laterite deposits), growth enhancements (seeping hydrocarbon deposits), specific species (locoweed in arsenic-rich soils)
- o Soil variations related to specific rock types at depth and associated mineral deposits
- o Clays uniquely related to hot water-rich fluids responsible for emplacement of certain metal deposits at depth (some types of copper-molybdenum and copper-gold deposits)
- o Rock types inherently associated with specific mineral deposits, where the rocks are visible or indicated at the surface
- o Structural features of several types, each of which can often be recognized by surface expression; examples are linears (faults and fractures) and circular features (domes or craters)
- o Water in lakes or streams (geochemical tracemetal composition in the most commonly used surface exploration technique in early stages of many metal deposit discoveries)

Ocean Research and Services

The satellite services of importance to marine science and the sea-going industry are navigation, communications, and remote sensing. Often these three functions are complementary; the capability, for example, to position science data precisely or to communicate information quickly is frequently coupled with the acquisition of data so closely as to become an indispensable ingredient. While the sensing function is of obvious value, it should be recognized that the navigation and communications functions provide

such valuable services that they rival environmental sensing in importance.

Navigation and communications are discussed elsewhere, but it should be emphasized that only a satellite-based system will provide the positioning accuracy required for science and industry on the high seas.

Communication is critical to research operations. Until the advent of satellite relays, both operational communications and data exchange were erratic.

For ocean research, remote sensing satellites are both a blessing and a frustration. Basic physical principles limit ocean observations. The penetration of an electronic signal into the water varies with frequency. In no case is it large compared to the average depth of the ocean. Remote sensing techniques presently can probe only the upper thin film of sea water. At depth, it is necessary to infer from the surface manifestations that can be observed. Work should continue to develop sensors to measure directly more oceanic factors of interest, both at the surface and to moderate depths. Since the ocean is active biologically, chemically, and physically in the upper few hundred meters, being able to sense as deep as the permanent thermocline would be both extremely useful and conceivably achievable. Examples of the factors to be sensed are the major fractions of the biological population, carbon dioxide, heavy metals and organics common in pollutants, and the nutrients (NO_x , PO_x , SiO_2) on which the oceanic food chain depends.

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In spite of current limitations, remote sensing of the ocean has some important advantages over conventional shipborne oceanographic sampling. A satellite can scan a very large area, and, by proper selection of orbital characteristics, the area of scan can be moved to provide global coverage at a fast rate compared with most other methods. Alternatively, the scan can be held in one spot so that synoptic, time-series observations can be taken. While there are trade-offs among such things as area of scan, repetition rate, and resolution, even rudimentary remote sensing can generate a mass of coherent data that is orders of magnitude larger than is possible, even from a fleet of oceanographic research ships. Because of this, only by the use of satellites can ocean problems of regional or global scale be realistically attacked.

The high-volume data output from remote sensing systems entails specialized data handling technology if the information is to be of practical value either to the oceanographer or the maritime industry. In fact, the utility of the information will depend as much on its ease of use and timeliness as on the quality of the data. This extends into every facet of data processing, selection, preprocessing, formatting, transmission, and archiving.

The provision of what are collectively called "ocean services" involves the translation of raw data into forms more usable by laymen, and, as a rule of thumb, the less sophisticated the customer, the more critical this translation function becomes. A short list of ocean services would include military activities (routine operations, undersea and antisubmarine warfare, specialized tasks); ocean shipping (both design and operations); offshore oil and minerals (structure design and operations); fishing (stock management and harvesting); recreation (fishing, boating); and coastal engineering (both routine and catastrophic effects). Demands range from the general to the extremely specific. At one end of the scale archives of data on which to base ocean structure design are needed, as are a broad knowledge of the patterns of weather, waves, and currents. At the other extreme are such things as spot weather/sea forecasts, ship routing, ice predictions, and fishing voyage guidance. The government and commercial providers of these ocean services face a formidable task, in which remote sensing plays an increasingly important role.

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Materials Processing

Manufacturing in space is in an altogether embryonic stage of development, especially when compared to satellite communications and remote sensing. The subject separates naturally into two parts. The first is concerned with the exploitation of a microgravity environment, either for the manufacture of relatively small quantities of high-value material or for study leading to a better understanding of the physics governing a manufacturing process and superior ways to do it on the ground. The second deals with making things in space to be used in space. Exploitation of microgravity environment has received most of the attention to date, space manufacturing in the second sense being of interest for the much longer term.

In the field of materials processing, the major advantage of the space environment is the absence of gravity and the corresponding effects on processes that are appreciably affected by earth's gravity. Before industry will make serious investments to investigate the advantage of microgravity, it must first identify potentially profitable products that can be made or enhanced only by a process conducted in space. For example, metal alloys have variations in properties caused by sedimentation, a gravity effect. Making these in space could produce more homogeneous materials and eliminate such variations. Growing crystals in a weightless environment produces larger crystals than is possible on earth. The purity of glasses can be improved by using a containerless process, eliminating the contamination problems of earth processing.

In pharmaceuticals, the separation and collection of biological substances can be done by continuous flow electrophoresis--a process complicated on earth by gravity-caused convection and buoyancy effects. It has been argued that operating an electrophoresis system

in space would enable separation of such materials in much higher quantity and greater purity than possible on earth. Two private firms have entered into joint endeavor agreements with NASA to develop the necessary processes, products, and business arrangements that would lead to commercial operations during the latter part of this decade. In both instances, the private firms are funding the experiment and space hardware. NASA is providing flight opportunities and services as incentives. If these programs prove successful, it is projected that commercial production of a high-value biological product (now under development) will begin in 1987. It is further projected that by 1995 a production plant growth from 13,000 pounds and 3.5 kilowatts of power to 169,000 pounds requiring 45 kilowatts will be needed.

Although commercial interests will most likely fund their own processes and product technology, there are areas in which technology developments would encourage industry to find products and processes of interest. Advances are needed to make possible adequate long-term, cost-effective power with attendant heat rejection and to improve the utilization of man in the maintenance and operation of space systems on a continuous basis, i.e., zero gravity hand tools, general purpose fixtures and test apparatus, and other life support services.

Except for purely conceptual studies, no spacecraft specifically dedicated to space manufacturing have been developed, so it is not possible to extrapolate to the future. There are, however, identifiable technological problems that will almost certainly arise in addition to those connected with the maintenance of the zero-g environment. Many manufacturing processes require large amounts of power--some estimates, specifically those related to space manufacturing, run into megawatts. The generation and utilization of large amounts of power imply the rejection of large amounts of heat. Also, many processes result in waste products that must be disposed of.

The shuttle will continue for a long time to serve as a basic experimental facility for microgravity research. For many processes, however, the shuttle flights are too short and too crowded, in the sense that other activities going on can interfere with the microgravity experiment. In the long run, a longer duration facility, capable of both manned and unmanned operation, will be required. This may be provided by a large manned platform or space station. In the more distant future, unique facilities dedicated to specific processes may emerge.

Technology Development Desired by Civil and Commercial Users of Space

A discussion of payload and spacecraft technology needs appears in Chapter VI. Listed here are the areas the Civil User Panel believes offer the most promise for accelerating the uses of space for practical and applied purposes:

- o High primary power with necessary heat rejection
- o Large aperture scanning and beam-forming antennas and associated feeds--10 to 20 meters with surfaces and feeds supporting UHF to millimeter wave use and the corollary control and stabilization devices
- o Data-handling, assimilation, and archiving systems--gigabit data streams with particular attention to architectural partitioning between on-board and ground processing
- o Payload technology--both basic and applied research directed at developing improved sensors and interpreting what they are observing (including cameras, radars, accelerometers, repeaters, associated preprocessors)
- o Cryogenic cooling and refrigerant systems--a few degrees Kelvin with multiyear lifetimes
- o Propulsion--"upper-stage" total impulses suitable for orbital plane changes of multipurpose platforms as well as ascent from low earth orbit to geostationary orbit and return
- o Spacecraft autonomy--application of artificial intelligence to spacecraft that can monitor and maintain themselves under routine and certain adverse circumstances
- o On-orbit servicing technology--manned maintenance, repair and calibration of spacecraft starting with space shuttle capabilities and extending towards manned space stations and attendable free flying platforms
- o Contamination control--prevention and elimination of sensor interference from debris and dust, stray light, unwanted heat, and gases

V.

Military Space Technology Forecast and Needs

The 1958 National Aeronautics and Space Act established the existing bifurcated U.S. space program in which NASA conducts government civil space programs and the Department of Defense (DoD) conducts military space programs. Several other governmental agencies (such as the Departments of Agriculture, Energy, Commerce, and Interior) have important roles in the U.S. space program, but NASA and DoD have primary responsibility for structuring nearly all of the programs.

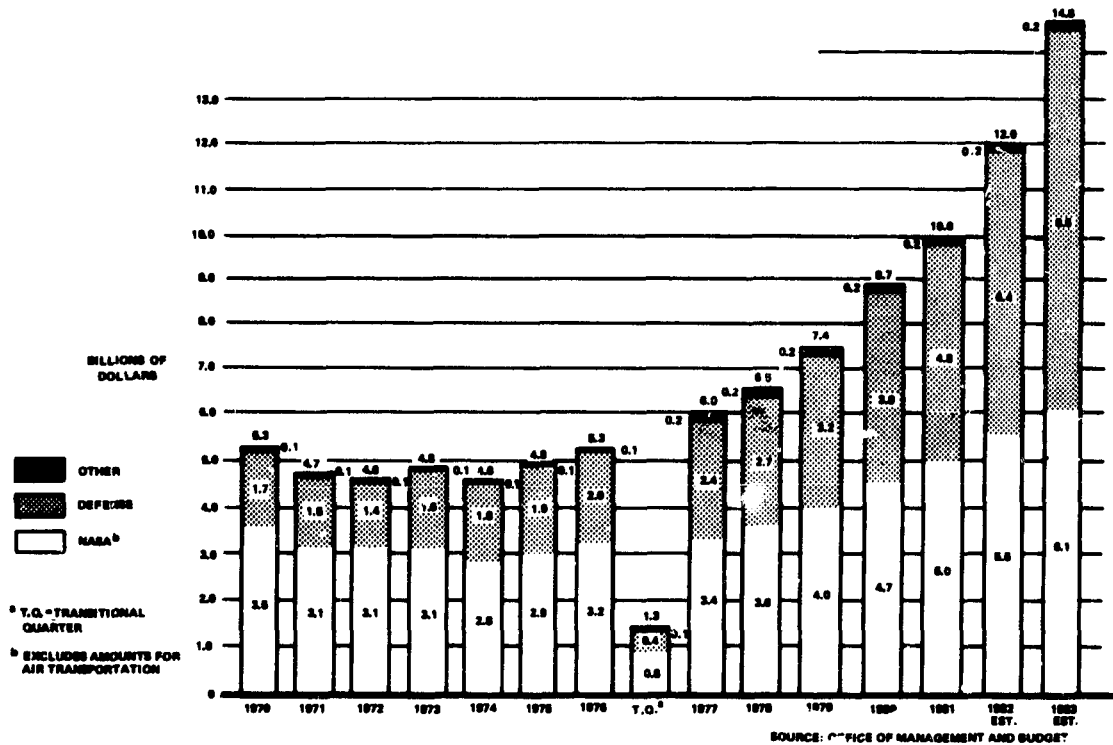
Over the past several years a number of issues have arisen concerning this bifurcation and, in particular, the degree of interaction between NASA and DoD in pursuit of their objectives. Three factors are bringing these issues into increasing prominence: the emergence of the space shuttle as the single launch system for all U.S. spacecraft, civil and military; the administration's intention (as stated by the Presidential Advisor G. A. Keyworth in Science, 13 August 1982) to "move the federal government out of the areas of development and commercial demonstration activities, except where the government is the customer...;" and constrained budgets which have caused NASA to scale back new civil space initiatives, while at the same time DoD's space budget is growing rapidly.

The military space program under the auspices of DoD is conducted primarily by the Air Force (though defense agencies, such as the Defense Advanced Research Project Agency, and other research divisions of the armed services also have a role). This program has gradually demonstrated the importance of space systems to various kinds of military operations and therefore, in recent years, the DoD budget for space programs has grown larger than that of NASA: for FY 1982 it was \$6.4 billion, compared to \$5.5 billion for NASA as shown in the following chart.

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U. S. Space Budget — Budget Authority FY 1970-1983

(May not add because of rounding)



The 1982 DoD space programs include: military aspects of the space shuttle program (including the inertial upper stage, modifications to Vandenberg Air Force Base for shuttle launches, and construction of the Consolidated Space Operations Center for command and control of DoD shuttle flights); development, acquisition, and operation of systems for communications, navigation, meteorology, surveillance, warning, and space defense, all with associated ground support systems.

The recognition of the increased integration of operational space systems into the military force structure has led to establishment of a new Air Force Space Command, which became operational on September 1, 1982. This command will have operating authority and responsibility and will provide a link between the space-related research, development, and acquisition process and its operational users.

During 1982 the Air Force also created within the Air Force Systems Command a new Space Technology Center at Kirtland AFB, New Mexico, that will coordinate the space research and development work of the Rocket Propulsion, Geophysics, and Weapons Laboratories and report to the the Space Division Commander, who will also become the Vice Commander of the Space Command.

The military use of space is steadily expanding and assuming an ever greater share of total U.S. space activities. To insure the effectiveness of this expansion, the DoD will have to increase its program of research and applied technology and thus intensify its need for the kind of support that OAST can provide.

DoD Space Technology Needs

Realizing the necessity for advanced technology for support of future space missions, in December 1979, the Air Force initiated preparation of a Military Space Systems Technology Model. The purpose of the model is to link the military space mission requirements with their related technology needs and to communicate these requirements and needs internally within the Air Force, as well as to other DoD organizations, to NASA, and to the industry.

To ensure that this does in fact happen, successively updated editions of the model are planned with a systematic process of reviews by relevant laboratories, by military space users and by the industry. The industry's reviews are carried out through a Space Systems and Technology Workshop cosponsored by the National Security Industrial Association and the American Institute of Aeronautics and Astronautics. This workshop provides industry specialists with a cohesive summary of future military space systems concepts together with the needed technology development programs and, in turn, provides industry's evaluation of these concepts and the applicable technological solutions.

The first edition of the Military Space Systems Technology Model consists of four volumes and was published in January 1982. The first of these volumes reviewed U.S. policy and strategy of space use, identified space-related mission needs in the 1985-2010 time period, and presented operational and functional mission rationale. The second volume described space system concepts derived from the identified mission requirements, stated the corresponding technical needs, and provided performance and risk estimates together with potential IOC dates. The third volume forecast technological trends by 14 functional disciplines and presented a discussion of each in terms of relevant figures of merit and state-of-the-art projections. The fourth volume compared these state-of-the-art projections with the technical needs and schedules of Volume II and identified various intertechnology trade-offs. The fifth volume presents an unconstrained technology roadmap leading to the satisfaction of system

concepts requirements of Volume II and identifies the technologies with high pay-offs.

The model is a statement of needed technological advances and priorities that may be used to formulate an approved space technology program plan (the sixth volume, which is scheduled for publication in 1983, is expected to contain such a plan). These advances, generically arranged, are sought by the mid-1990s and are listed below. A more detailed listing of military space technology needs is given in Appendix B.

- o Information Processing: On-board, radiation-hardened, fault-tolerant processors, capable of handling up to 10^9 operations per second with memories capable of storing up to 10 gigabits of information. Fault-tolerant software utilizing artificial intelligence and adaptive techniques for self-analysis, event recognition, discrimination, data compression, and the selection of significant information for transmission to the ground.
- o Propulsion: Chemical or electrical systems capable of efficiently providing large velocity increases for orbital transfer (including orbital plane changes), evasive maneuvering, orbital construction and maintenance and also for position and attitude management over a long time. Efficient engines (with specific impulse of about 380 seconds at sea level and more than 465 seconds in vacuum) with high thrust-to-weight ratios, capable of responding rapidly and able to lift large payloads at low cost. Control of contamination and emittance of the exhausted material.
- o Structures: Large (up to 100 meters) deployable antennas capable of maintaining precise figure control and multibeam operations. Supporting structures for light, large optics, and optical systems capable of maintaining the required dimensional stability. Innovative design and assembly techniques for large space structures.
- o Communications: Microwave and optical systems capable of 5 gigabit-per-second transmission rates. Reliable, long-life (more than 10 years), solid state, high-power amplifiers both Impatt and GaAsFet.
- o Thermal Control: Reliable, lightweight, long-lived (up to 10 years) heat exchange systems and refrigerators capable of cooling infrared focal planes and various communication and high-power radar components. Variable conductance diode heat pipes (10-500°K). Lightweight radiators (1-2 kilograms per square meter).

OGR. 1

- o Sensors: Large (diameter 2 to 5 meters), lightweight optics. Large charge-coupled devices (10^7 detectors) for short wavelength, medium wavelength, and long wavelength infrared. Small (1 gram, 1 watt), radiation-hardened transmit-receive modules for phased-array radars.
- o Guidance, Navigation, and Control: Autonomous, long-lived (over 7 years) systems for satellite navigation (accuracy of about 10 feet) and for precise pointing of sensors and weapons (accuracy of about 0.2 microradians) and also for figure control and deployment of large structures. Support of rendezvous docking and robotic maintenance operations on orbit.
- o Power: Long-lived (more than 10 years), low-weight (15 watts per pound), high-power (more than 35 kilowatts) solar power systems with high radiation resistance. High specific power batteries. High-voltage (greater than 100 volts) power distribution systems.
- o Materials: Materials with high specific stiffness and high thermal deformation resistance for large space structures. Relatively high-temperature (about 18°K) superconductors.
- o Man in Space: Remedies for motion sickness, hypervolemia, and calcium loss caused by absence of gravity. Long-lived, lightweight life support systems. Lightweight and less cumbersome suits for extra vehicular activities.
- o Space-Based Nuclear Reactor: High-power (1 to 100 megawatts) and power density (larger than 50 watts per pound) nuclear electric power systems.

NASA-Military Technological Interaction

The military space systems technology model is patterned after the similar NASA model that also provides a list of needed technological advances. The two models together could provide a basis for selection of technological programs of common interest to NASA and the military. Such programs are obvious candidates for joint cooperative efforts and provide a solid foundation for meaningful and productive interaction between the two agencies.

Until recently, the interaction between NASA and the military in the area of fundamental research and applied technology has not been close. Two formal mechanisms have been established for both decision making and information exchange: one, at a highly classified level between delegates of the NASA Associate Administrator, Aeronautics and Space Technology, and the Under Secretary, Defense Research and Engineering, and the other through the supporting Research and Technology Panel of the Aeronautics and Astronautics Coordinating

Board (AACB). This panel oversees the NASA/DoD Space Technology Interdependency Group (STIG) that evolved from a working group established in 1973 to exchange status briefings on programs of mutual interest.

A substantial amount of technical interchange also occurs informally among scientists and engineers working in similar areas within their respective agencies, but this process does not prevent a duplication of programs and does not allow for easy use of the pertinent information when planning or developing new systems.

There is also a history of joint technology programs including flight vehicles such as SCATHA (Satellite Charging at High Altitudes), a USAF test vehicle that carried some NASA experiments, LDEF (Long Duration Experiments Facility), a NASA test vehicle that will carry about 14 DoD experiments, and ground technology development programs in which each agency develops a parallel approach (e.g., solar cell research where the DoD develops gallium arsenide and NASA develops silicon cell technology). Most recently, the Defense Advanced Research Projects Agency and NASA/OAST agreed upon a joint three-year study of space nuclear reactor technology.

In 1982, however, STIG's charter was broadened to include oversight and guidance for joint space technology development programs that will culminate in verification and/or validation on either NASA or Air Force space test vehicles. A Memorandum of Understanding between NASA and the Air Force Systems Command (Appendix C) spells out the broadened STIG charter.

This new mechanism for the cooperative development of joint technology programs appears to be driven by the previously discussed budgetary pressures and appears to have the support of the top management of both organizations. Still, while NASA personnel assignments are fairly stable, their uniformed personnel counterparts within DoD routinely change due to the normal military rotation process. To help ensure continuity of the agreement, a policy statement at a high level of NASA and DoD strengthening the STIG charter is highly desirable.

STIG intends to use the two complementary space technology models, thus assuring that the selected programs will be important to NASA and the Air Force. Indeed, six programs already have been chosen for joint support starting in 1984 and all appear to be essential to the future space missions of both organizations. These are: synthetic aperture radar; radiation hardened electronics; control of large space structures; solar cell array development; spacecraft contamination; and autonomous systems.

Three additional programs currently under consideration could result in an eventual commitment of about \$15 million per year by each agency to joint efforts.

Thus, in spite of its short existence, STIG has made significant progress towards improved NASA-military interaction in the fundamental research and applied technology area. To continue this progress, it is essential that NASA and the Air Force's new space organization maintain interest in pursuing this cooperative effort.

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VI.

Technology Needs

In the preceding sections, projections for civil, commercial, and military space applications are discussed. Much of the technology needed for these applications is common among the users. In this section, technology needs are defined in the following areas:

- o Cost Reduction
- o Propulsion
- o Structures and Materials
- o Data Processing
- o Sensors/Payloads
- o Communications
- o Power
- o Environmental Control
- o Navigation, Guidance and Control
- o Man in Space
- o Survivability

Under each technology area a general discussion of the applications that drive the required technology improvements is given, and then the improvements in the performance required for both near-term and future missions are presented in a table for each area. The performance required is separated into incremental and "breakthrough" performance improvements. Substantial technology gains are needed in all areas.

Cost Reduction

Escalating costs in the development and manufacture of payloads and spacecraft and transportation to orbit, including launch and orbital transfer, are the most critical barrier to the use of space, especially for the commercial sector. Development and placement of an operational system on orbit routinely can cost more than \$100 million. Part of this problem is the nature of spacecraft development; spacecraft tend to be one of a kind or, at best, small multiples of a kind, and the high cost associated with failure to meet

mission requirements places a high premium on reliability and leads to redundancy in design.

The cost of operating in space was a recurring concern during the workshop, permeated the panels' discussions of technology needs, and is evident in the recommendations for research in several of the disciplinary areas. A general technology recommendation, therefore, is that OAST should identify the major space system cost drivers and attack them by undertaking research and providing the technology to reduce the cost of the use of space.

Propulsion

Propulsion is basic to all space system concepts for both civilian and military applications. Propulsion is required for launch vehicles, orbital transfer vehicles, planetary probes, and auxiliary systems, as well as special needs that may develop for space station orbit maintenance, transfer, and attitude control. Heavy payloads proposed for launch in the 1990s will demand additional emphasis on efficiency in propellants and engines. Advanced, high-specific-impulse propulsion systems for orbital transfer vehicles will be required to guide large structures to geosynchronous orbit. Also, since the start of the space shuttle main engine development, little has been done to advance the technology of liquid rocket engines. The cryogenic high-pressure LOX-Hydrogen and LOX-Hydrocarbon rocket engine offers high payoffs, and this area is probably the single most important area for long-term work in propulsion.

In the 1983-2000 time frame, an advanced orbital transfer vehicle is essential for use with the space shuttle to place payloads into high earth orbits (up to geosynchronous) and to impart spacecraft on planetary excursions.

The following table lists the perigee stages that are expected to be in use during the 1980s. All except Centaur use solid propellants and therefore are designed to operate over a narrow range of payload capability. The table lists the weight these stages will place in orbit when used to establish geosynchronous transfer orbits. During the late 1990s new stages will be needed in the range of 3500-9000 pounds. To provide flexibility and to achieve significant reduction in the operational costs for delivery of payloads to synchronous orbit, liquid bipropellant upper stages will be needed.

UPPER STAGES FOR SHUTTLE IN 1980s

<u>NAME</u>	<u>LENGTH, FT</u>	<u>STAGE PLUS SPACECRAFT</u>	<u>GEOSYNCHRONOUS TRANSFER</u>
		<u>WEIGHT, LBS</u>	<u>ORBIT WEIGHT, LBS</u>
PAM-D	8	11,000	2400 to 2750
PAM-II	9.6 - 10.4	13,300	3500
PAM-A	7.5 ⁽¹⁾	17,000	4400
PAM-VI ⁽²⁾	6.9 ⁽¹⁾	30,200	9065
IUS	16.75 ⁽³⁾	63,700 ⁽³⁾	16,500 ⁽³⁾
Centaur	29.1	56,500	32,200 ⁽⁴⁾

Notes:

- (1) Does not include length of spacecraft.
- (2) Perigee stage for Intelsat VI.
- (3) IUS contains both perigee and apogee stages; length includes apogee stage; weights are estimated to describe IUS on a comparable basis.
- (4) Estimate includes 7000 pound Centaur stage plus 11,700 pounds of propellant; weight in synchronous orbit is 13,500 pounds.

Four different propulsion types that will be used in future spacecraft are:

- o High-pressure LOX-Hydrogen and LOX-Hydrocarbon rocket engine developments in several thrust ranges
- o Propulsion systems using chemical laser propellants, primarily for military missions
- o Improved performance versions of the re-usable strap-on boosters for the STS
- o Long-lived or plasma drive systems with higher thrust for continued exploration of the solar system and for plane change for future space systems

Electric propulsion for orbital transfer vehicles could supplement

the transport of large, complex-geometry structures when long transfer times are not a drawback. Specific impulse, on the order of 1500 seconds with thrusts from millipounds to 100 pounds, may be most effective. Increased rocket engine performance that reduces weight by using high-energy cryopropellants will require advances in long-term cryostorage. Heavy lift launch vehicles with increases in specific impulse could result in significant weight savings for delivery of heavier payloads on orbit as well as lower the total launch costs. Particular emphasis should be placed on propulsion elements for an "on demand" reusable launch vehicle for the replenishment of space resources. Developments can also be foreseen involving nuclear and laser devices, as well as rail gun and laser propulsion systems. In addition, new energy sources (e.g., metallic hydrogen) may be discovered and applied.

PROPULSION

Desired Advances

- * Launch Vehicles
 - Specific Impulse--380 secs. at sea level
 - 465 secs. in a vacuum
- * Orbital Transfer Vehicles
 - Specific Impulse--330 secs., storable fuel
 - 475 secs., cryogenic fuel
 - Thrust--up to 20,000 lbs.
- * Electric Propulsion
 - Specific Impulse--1500 secs.
 - Thrust--0.01 to 100 lbs.
- * Cryogenic Storage Lifetime--3 years
- * Reduced Contamination and Emittance

Technology Needs

Incremental Gain

- * Propellant transfer
- * High-energy, low-thrust engines
- * High-thrust hydrocarbons
- * Electric propulsion (low thrust)
- * Low-cost, reliable launch to geosynchronous orbit
- * Electric-ion propulsion for station-keeping
- * High-specific impulse propulsion for station-keeping

Potential for Large Gain

- * Aerobraking
- * Pumps for low-thrust engines
- * Cryostorage in space
- * Electric propulsion (high thrust)
- * Combined life support, energy, storage, propellents

Structures and Materials

Proposed very large space-fabricated, -assembled, or -deployed structures will require innovative designs using advanced composite and metal matrix materials of high specific stiffness and low weight. Advanced thermal protection systems utilizing hot structure technologies will ultimately be required for protection upon re-entry for future heavy lift reusable launch vehicles. One of the most demanding challenges is the reduction of launch costs by lowering overall weight with the use of lightweight materials and structures.

Future spacecraft will include large-aperture space antennas, large solar arrays, and possibly a space station or platform. Requirements for increased pointing accuracy, precise contour control, long-term dimensional stability, and more effective thermal control are expected. These lead to sometimes conflicting structural requirements such as large size, weight constraints, relatively high stiffness, and minimal thermal distortion. Innovative design approaches and technological advances in some areas will be needed to effectively meet these challenges.

It is an important design objective for elements of present spacecraft, such as optics and antenna support structures, that deformations due to thermal gradients be kept near zero. Composite materials, which also offer an attractive weight-to-stiffness ratio provide a solution for the problem of thermal deformation but create other problems in areas of moisture absorption, long-term stability, and space radiation effects. Continued research is needed for these materials. The newer metal matrix materials are not affected by moisture and offer significant improvements over resin matrix materials for future space applications. However, work is needed in fabrication and manufacturing methods if these materials are to be used in future spacecraft.

The primary structural design drivers will be control system constraints, long-term dimensional stability, and resistance to thermal distortion. The interaction of structural dynamic deformations with the control systems used to stabilize and maneuver large space satellites will be important.

For military applications, uses of lightweight materials will include large antennas of the order of 10 to 100 meters in diameter. These may be either deployed or assembled on orbit using light yet very stiff structural elements. Lightweight, large (10 meters) precision optics are needed in deployable or easy to assemble form. For a variety of missions, methods must be devised for effectively packaging these large deployable payloads. General characteristics for spacecraft and structures include:

- o high specific stiffness
- o high thermal and electrical conductivity

- o near-zero thermal expansion
- o no moisture absorption
- o no out gassing or contaminating by-products
- o resistance to space radiation effects

For commercial applications, the future technology drivers in this field stem from demands on process control for in-space manufacture and purification of materials as well as the need for lightweight composites to lower launch costs and the need for figure and vibration control of large antennas. The government requirements will be based on the technology needed in support of manned space stations. Many technologies will be employed--some needing incremental improvements, others requiring "breakthroughs." Key areas are the composition and erection of main structural elements, thermal control and protection, heat pipe and coolant distribution improvements, lubricant development, inflatable structure application, and simulation testing.

Also, because of the uncertainties attendant with structural scaling and the difficulty of full-scale ground testing of the large spacecraft that are envisioned, new test concepts (probably combining ground and flight aspects) will have to be developed.

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For all applications, reduction of contamination and erosion of materials, protection from and resistance to solar and nuclear radiation, especially in heat transfer surfaces and microelectronics, and data on the effects of radiation on composite materials are important research needs.

There is a need for a base of data and information on the performance of a wide variety of materials in the space environment. Large structures require long-term dimensional stability and resistance to thermal distortion. Composite materials offer attractive ratios of weight-to-stiffness and thermal deformation characteristics but are subject to moisture absorption and space radiation effects. New metal matrix materials offer improvements over resin matrix materials but may be subject to problems from other effects of the space environment.

It is recommended that OAST undertake a program to characterize the performance of materials in the space environment.

Greater understanding is needed in the following areas:

- o Contamination--from out gassing, life support, and propulsion system products.
- o Erosion--due to debris, micrometeoroids, high-energy particles.

- o Radiation--solar and nuclear radiation. Solar effects on radiators and solar panels; long-term effects on materials, particularly composites; radiation effects on the total spacecraft/payload, especially effects on microelectronic devices.
- o Plasma effects -- possible cause of spacecraft charging and electrical noise in geosynchronous orbit.

STRUCTURES AND MATERIALS

Desired Advances

- * Optics--up to 25 meters diameter
- * Deployable antennas up to 100 meters, figure control 0.01 wavelength
- * High specific stiffness
- * High resistance to thermal deformation
- * Service temperature greater than 700°K
- * Lifetime in space--10 years
- * Lighter Weight

Technology Needs

Incremental Gain

- * Hot structures
- * Lightweight optics
- * Advanced composites materials technology

Potential for Large Gain

- * Large deployable antennas
- * Spaced-based fabrication, assembly, and deployment
- * Reusable tanks/recoverable vehicles

Data Processing

Data management--the process of collecting, processing, archiving and distributing the data to users that need it--has been a primary limitation to both scientific and commercial exploitation of satellite remote-sensed data.

The problems attendant with the large data sets collected by the Landsat satellite series, the Seasat series satellite mission, and the NOAA polar orbiter and GOES satellite series have been identified,*

*Committee on Data Management and Computation, Space Science Board, Assembly of Mathematical and Physical Sciences, National Research Council, Data Management and Computation, Volume 1: Issues and Recommendations, National Academy Press, Washington, D.C., 1982.

and recently, efforts have been initiated to resolve the problem of handling the extremely large amount of data gathered. Many uses for the data require real-time or near-real-time data handling. The problem involves the data communication links, computers required to process the data, data storage, interactive terminals to allow perusal of data sets and the software systems required to process the data, extract the desired information from the data, and sort and distribute the information to the user.

In addition to the ability to handle global data sets in a near-real-time mode, the cost of producing the data in a usable form must be reduced. At present, the cost of data handling inhibits commercial exploitation of the data. This is the case currently with Landsat data, whose cost is projected to increase by a factor of five due to elimination of the federal subsidy.

The Committee on Data Management and Computation of the National Research Council's Space Science Board concluded that there are no fundamental barriers to achieving a substantial improvement in scientific and commercial data management during the 1980s. However, a strong technology development effort is required.

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On-Board

Developments in digital microelectronic devices have an important impact on future spacecraft programs. The very high speed and the large-scale integrated circuit programs will accelerate the rapidly changing field of microprocessor technology and make practical a new generation of powerful, high-speed spacecraft computers and data processors. A fundamental need is the determination of the most efficient, cost-effective balance between on-board and ground data processing. Expansion in on-board signal and data processing is needed to meet the needs of multiuser and multimission advanced space systems. Deep space probes, earth surveys, and weather mapping can generate more data than it is practical to send to the ground for processing. On-board processing is essential. Typical functions are image processing for infrared, optical, and synthetic aperture radar sensing systems; signal identification, correlation, and location for RF sensor systems; communication system activity monitoring and switching; and data thinning and compression. Such functions require high-speed, wide bandwidth processors and routing, and mass data storage and retrieval.

On-board processing may also be utilized to provide autonomy and to significantly improve satellite reliability, survivability, and endurance. In order to satisfy these goals the microelectronic components must be hardened to withstand the natural and man-made radiation environment.

Very-high-speed integrated circuit technology, laser recording, and acousto-optical processing are key issues. Present on-board processing systems are limited to about 0.5 million instructions per

second (MIPS), random access memories (RAMs) with access times around 100 nanoseconds (nsec), and data storage of 300 megabytes. Future systems should have capabilities for 200 MIPS, 15 nsec low-power RAM memory and data bases as large as 10^{12} bits.

Capability exists for the production of commercial large-scale, medium speed, integrated circuits in high volume. However, research is required to provide the technology for relatively low-volume, space-qualified components to provide higher speeds, radiation resistance, and packaging for heat dissipation. Laser disk recorders require research into erasable (annealing) processes. Fault tolerance and error detection and correction techniques need to be incorporated into the individual devices. Improved design methodologies are needed for integration of existing stand-alone software packages and adaptation to space environmental conditions.

There is currently a need for on-board annotation of the satellite data with such information as ephemeris, attitude, atmospheric moisture composition, and cloud cover to avoid cumbersome ground-processing and delays attendant in collecting the requisite data sets. The development of on-board computer capability including space-rated large mass storage, high-speed data-handling technology, and the software algorithms for conducting data preprocessing is essential to achieve maximum efficiency in ground-based data handling.

At present, NASA has under way a project called the National End-to-End Data System (NEEDS), which is exploring the conceptual ideas required to bring together large data bases and transfer them to a central archival point. On-board satellite registration and annotation of data is a fundamental concept that should be included under the NEEDS project.

Ground Data Processing

Ground data processing is rapidly becoming the major cost element in space operations. Its future can be categorized in three interrelated research activities.

The most fundamental involves the physics-of-state detection and data changes associated with any phenomena that can represent binary state. As the phenomena is pushed to smaller scales, the characteristic execution times will decrease and storage densities will increase. If we are to achieve instruction execution rates much beyond 10^{10} instructions per second, it will be necessary to utilize physical phenomena at the molecular level.

The pacing technology that currently dominates the state of the art of computing is the engineering of processing hardware. Today there are hardware devices capable of 250 MIPS, 500 megabytes of fast access storage, and 37.5 megabytes per second transfer rates on a network. The technology initiatives required to improve this performance are: VHLSIC, microprocessor technology, mass storage and retrieval, image

processing, laser recording (including rewrite capability), optical processing, fault tolerant computers, and networking devices. Over the next 15 years hardware performance should increase to 2 billion instructions per second, 10^{12} to 10^{14} fast access storage, and 850 to 100 megabytes transfer rate.

If this capability is to be used effectively, it is vital that software engineering technology keep pace. Current programming productivity is limited to 600 to 3000 source lines of code per man year. It is within reason to expect a tenfold productivity increase, and the design specification, testing, documentation, and configuration management can be automated to reduce the enormous investment now required to achieve a minimum of latent errors in operational programs. In addition, the following computer science technologies will dominate applications for the future: user languages for direct design specification to code translation, computer security, expert systems (data bases), decision aids, artificial intelligence, and voice data entry.

An associated item, regarded as a long-range technology requirement, is the development of large ground-based mass storage devices. Projection of the requirements for the data sets developed by high-resolution instruments that are becoming available for both commercial and scientific exploitation of satellite-sensed data require the storage of 10^{14} to 10^{15} bits of data.* Currently, there is not a clear leader among the technology options related to the mass storage requirements. Contenders include bubble memories and optical disk memories that use lasers for recording the information on both metallic media and on film systems.

It is recommended that OAST emphasize R&T to improve the data systems architecture required to allow rapid, frequent, and cost-efficient processing and production of global remote-sensed data.

* Committee on Data Management and Computation, Space Science Board, Assembly of Mathematical and Physical Sciences, National Research Council, Data Management and Computation, Volume 1: Issues and Recommendations, National Academy Press, Washington, D.C., 1982.

DATA PROCESSING

Desired Advances

- * Processor: data rate-- 10^3 - 10^4 million bytes/sec.
throughput-- 10^2 - 10^3 million operations/sec.
power--1 watt/million operations/sec.
- * Memory: capacity up to 10^4 million bits
access time--0.5-2 microseconds
- * Radiation hardness-- 10^6 rads
- * Fault tolerant
- * Coding gain--7.5 decibels for 10^{-6} bit error rate
- * End-to-end data mgmt. system--500-1000 million bytes/sec.

Technology Needs

Incremental Gain

- * On-board data processing, including improved microprocessor and bulk memory
- * Advanced software
- * Economic data handling
- * Timely availability of data (earth resources)
- * End-to-end data management system
- * Efficient data compression

Potential for Large Gain

- * On-board digital and optical processors
- * Artificial/machine intelligence

Sensors/Payloads

Rapid increase is expected over the next 10 years in the utilization of space-based sensors for the detection, identification, and tracking of targets located on earth, in the atmosphere, and in space. These sensors will be based on both optical and microwave techniques.

The anticipated required increases for military application in electro-optical sensitivity and accuracy will lead to a need for very large, lightweight optics as well as mosaic focal planes consisting of tens of millions of detectors. These sensors will be developed to operate at different wavelengths depending on the temperature characteristics of the targets and their backgrounds. Very large radars (tens of meters to possibly hundreds of meters antenna diameters) are also expected. These phased-array radars will operate from 1.2 to as high as 60 gigahertz and will require very small (1 gram), very power-efficient transmit/receive modules to operate for long periods of time (years) in the projected radiation environment.

NASA/NOAA commercial improvements in sensors and scientific/application payloads are needed in two directions: (1) improvement in sensor capabilities, and (2) the ability to make self-determinations of when data should be taken. Earth observation systems require better spectral and spatial resolution and new sensor systems to measure phenomenology not yet discernable by present-day technology. The types of sensors that are amenable to quantum jump improvements are microwave, both passive and active, visual and infrared, laser, and particle sensors. The new applications range from detection of ships and aircraft for traffic control, improved ocean phenomenology systems, and better detection of geologic and biologic forms, to improved weather analysis and forecasting. Along with improvements in sensors must come improvements in data interpretation. This must develop from more sophisticated ground truth correlations.

JGR.

SENSORS/PAYLOADS

Desired Advances

Electro-optics

- * Wavelength--multi-spectral
- * Focal plane-- 10^7 detectors, high temperature
- * Optical mirrors--1 to 3 meters diam., lightweight
- * Tunable filters--2.5 micrometers; polarization rejection 10^5

Radar/microwave

- * Frequency--up to 60 gigahertz
- * Power--1 watt per module
- * Weight--1 gram per module
- * Noise figure--2 decibels
- * Microwave radiometry up to 200 gigahertz, noise figure less than 5 decibels

Technology Needs

Incremental Gain

Electro-optics

- * Mosaic charge coupled device focal plane
- * Lightweight mirrors

Radar/microwave

- * Solid-state transmit/receive modules
- * Complete data extraction

Potential for Large Gain

Electro-optics

- * Tunable filters

Radar/microwave

- * Synthetic aperture microwave radiometry techniques
- * Lidar measurement

Electro-optics/Radar-microwave

- * Earth observation sensors/spatial-spectral resolution microwave/infrared/visual sensors
- * Image processing
- * Sensors for oceanographic purposes
- * Smart sensors--when, where, cull unwanted data
- * Earth resource identification algorithm for geologic/crop use

Communications

As shown in Chapters IV and V, improved communications systems are required both commercially and by the defense establishment. The field of communications pioneered the exploitation of space and there have been impressive gains in the ability to communicate with anyone, any time, and almost any place. Future applications require improved technology in the amount of data being sent or relayed and in the speed at which it can be delivered.

In the military arena, both privacy and information content demands are moving carrier frequency requirements to possibly above 100 gigahertz and assorted very large bandwidths to handle laser-communication capability. The same requirements are driving needed improvements in antenna designs and figure maintenance.

In the nonmilitary world, earth resource and environmental needs are providing very large data storage and transmission rates that were discussed under Data Processing. These require improvements in low-noise receivers, high-power linear amplifiers, signal processors, and more efficient and intelligent data compression techniques. Commercial applications continue to press for antennas that are both large and agile.

COMMUNICATIONS

Desired Advances

- * Frequencies--microwave to 130 gigahertz
- * Steerable multibeam antennas--44/20 GHz, 94/130 gigahertz
- * Transmission rates--up to 5×10^9 bits/sec.
- * Antijam
- * High-power amplifier life greater than 10 years
- * Voice bandwidth compression--10 decibels

Technology Needs

Incremental Gain

- * Higher frequencies
- * Laser communications
- * Multibeam antennas
- * High-power, high-efficiency traveling wave tube amplifiers
- * Antenna technology/
large, phased arrays
- * Low-noise receivers
- * Communication demodulation/
remodulation processors

Potential for Large Gain

- * Solid-state, high-power amplifier
- * High-power linear amplifiers, solid state amplifiers for Ku band transmitter

Power Systems

Spacecraft power systems include power generation, regulation, distribution, and energy storage. In all areas, advances will be required to meet future needs. Power requirements projections to meet future civil needs indicate a four- to fivefold increase over present-generation spacecraft by the year 2000, i.e., as much as 20-30 kilowatts. DoD studies of long-range technology needs show potential applications in the megawatt range. The ratio of peak-to-average power for certain missions, such as space radar applications, will be substantially higher than present practice (as high as 20:1). Providing for such peak power demands is a major driver for energy storage technology. This technology will also be driven by long-life (up to 10 years) and minimum weight requirements and will be a significant concern for autonomous spacecraft designs. Large flexible solar arrays, because of their relatively high power-to-weight ratios, will play an important role in providing higher power for future spacecraft, and their continued development will be an important part of our overall power systems technology program. JGR.

Emphasis should be placed on lightweight components, especially for energy storage. The development of an energy storage component that is significantly lighter than nickel cadmium (NiCd) or nickel hydrogen (NiH₂) batteries is critical to realizing higher power systems in high earth orbits. The high-temperature alkali metal systems developed by the Department of Energy may fill this need, but other concepts should be sought in both the advanced energetics and electrochemical areas.

The significant technology issues that require attention in the spacecraft power systems area are:

- o Solar Arrays: solar cell welding; high-performance thin cells; gallium arsenide cells; low-cost cells; radiation-resistant and nuclear- and laser-"hardened" solar cells and solar arrays.
- o Energy Storage: thermal mechanical packaging studies; lightweight, long-life NiCd and NiH₂ batteries; high-energy density alkali metal batteries; regenerative fuel cells; detailed studies for accurate comparison between energy storage systems.
- o Power Conversion and Regulators: high-power, high-voltage regulator development; radiation testing of metal oxide silicon field effect transistor (MOSFET) devices.
- o Power Distribution: comparison of approaches to power switch-gear nets; high-voltage power distribution concepts.
- o Nuclear Power Sources: system studies that make comprehensive comparisons with other power sources and address the total electrical power system.

P O W E R S Y S T E M S

Desired Advances

- * Batteries:
 - high specific energy up to 20 watt-hours/lb.
 - high power greater than 35 kw, 15 watts/lb
- * Solar arrays/cells:
 - large size--up to 250 kw
 - cell efficiency up to 22%
 - life greater than 10 years
 - radiation resistance up to 5×10^{15} electrons/sq. centimeter
- * Nuclear power systems:
 - high power reactor greater than 1 megawatt at 50 watts/lb
- * High-power distribution:
 - AC--120V, 10 kw, 100 watts/lb
- * Fuel cells:
 - power up to 1 megawatt, 65 watts/lb
 - life-- 3×10^4 hours

Technology Needs

Incremental Gain

- * Batteries/storage devices
- * Solar arrays/cells/concentrators
- * High-voltage distribution/
switching/regulation
- * Fuel cells
- * Efficient batteries
- * High-power distribution
- * High-power switches
- * High-power supplies

Potential for Large Gain

- * Nuclear power systems
- * Power storage wheels
- * Large solar arrays

Environmental Control

Environmental control deals with the thermal as well as the radiation and contamination environments of spacecraft. Significant improvements are required in both active cryogenic cooling and in heat rejection. The radiation environment poses unique problems in differential spacecraft charging and in degradation of microelectronic components. A serious concern for optical and other advanced sensors and environmental monitors is contamination, from propellant effluents, material out gassing, and particulates carried within the payload bay.

Spacecraft trends toward longer life, higher heat loads and fluxes, stored cryogenic propellants, increased use of infrared sensors, closer dimensional control, and the future involvement of man in operations and refurbishment will result in new requirements for thermal control. Methods and procedures for analyzing component/system interaction in the spacecraft thermal environment and knowledge of the stability of materials that are the mechanisms for energy dissipation and thermal control are primary needs. Also of importance is the development of concepts and devices for thermal control. The vulnerability of spacecraft to hostile laser weapons poses added problems for spacecraft thermal designs.

DGR.

In the area of thermal control analysis, future needs include:

- o Analytical processes to define and evaluate thermal control designs, coupling the space equipment segments to the environment.
- o Improved methods for analyzing laser effects, particularly in the high-flux pulsed model and in assessing effects of the reflected laser energy to secondary surfaces.

In the area of thermal control concepts and devices, future needs include advances in:

- o Low-temperature heat pipes (variable conductance, diode, and flexible).
- o Two-phase thermal management system (pump assisted heat pipe or vapor chamber).
- o Lightweight flexible fluid lines with zero leak disconnect capability (for system refurbishment).
- o Long-life low-temperature refrigerators.
- o Lightweight radiators (heat pipe augmented).
- o High-flux laser mirror cooling.
- o Cryogenic propellant storage and transfer systems.

Experiments in space will play a key role in providing technology readiness in the area of thermal control. Surface contamination effects, space charging information, demonstrations of new heat pipe and radiator concepts, and the evaluation of propellant storage and transfer systems will all require on-orbit testing.

For military applications, advanced optical sensors are particularly sensitive to contamination and must be closely guarded against contaminant coating of optical surfaces. As the need for cryogenics increases, long-life, efficient refrigerators must be developed along with lightweight heat rejection systems. Although spacecraft charging has been studied extensively through analyses of SCATHA* spacecraft experiment data, the problem periodically surfaces and must be designed out of future systems. Advances in designing and shielding spacecraft electronics for radiation degradation and single-event upsets is a generic problem that becomes more severe as LSI/VLSI technology for space use accelerates.

The long-range enabling technology demands in environmental control are driven by the need for sophisticated multi-man life support and environmental control systems for large space stations and, concomitantly, by the requirements for cryogenic refrigeration systems. These systems will have significant interactions with propulsion and thermal control requirements.

ENVIRONMENTAL CONTROL

Desired Advances

- * Refrigerators--10 years life; less than 10°K; 10% Carnot efficiency
- * Variable conductance diode heat pipes--10-100°K
- * Lightweight radiators--1-2 kilograms/sq. meter
- * Hardening

Technology Needs

Incremental Gain

- * Active cooling
- * Contamination control
- * Charging
- * Thermal management
- * Radiators (puncture protection)
- * Erosion control

Potential for Large Gain

- * Man in space/closed ecology
- * Cryogenic refrigerators

* The USAF Satellite Charging at High Altitudes Experiment

Navigation, Guidance and Control

This area encompasses the technology for satellite stability, pointing, maneuvering, attitude determination and control, navigation, and the devices needed to provide these functions for future spacecraft such as multipayload articulated spacecraft, space-based lasers, large antennas, space platform, and other large structures.

Control system design methods for large space structures (LSS) are just beginning to evolve, but proven methods do not yet exist. Such systems can be designed using classical synthesis techniques, and most companies involved have developed adequate synthesis programs. However, this is laborious and, perhaps, could be replaced advantageously. For example, linear quadratic gaussian (LQG) design methods have not been developed for such spacecraft but might be a reasonable approach.

The standard approaches to Kalman Filter and Extended Kalman Filter design are well known and will play a role in future applications for attitude determination and navigation through the year 2000. However, as more sophisticated computers are developed for both on-board and ground-based processing of navigational and attitude measurements, algorithms with improved accuracy and computational efficiency should be developed. In particular, the application of parallel and vectorized architecture can provide significant improvements in performance, but may require that special algorithms be developed.

The chief commercial concerns in this area are involved with requirements of navigational systems. Such systems will support all types of ground and airborne transportation vehicles and must be developed at low cost and with light weight.

Government requirements for advancement come in large part from the guidance and control demands of large space structures. Specifically, the control and pointing of large structures, as well as their ability to maintain figure control where necessary, requires demonstration programs to help find the best way to perform such tasks. The best way, or combination of ways, to control and point these structures and the component necessary to perform or assist (such as dampers) may not yet be developed. In addition, important gains in automation, fault tolerance, and on-board estimation must be made for military and nonmilitary systems alike.

For military systems, accurate pointing of space-based antennas and weapons requires on-board knowledge of the satellite position. That information is currently made available from the ground, but increasing requirements with regard to system survivability and endurance lead to the requirement that navigation and guidance functions be performed autonomously on board the satellite. The navigation accuracy requirements vary with the mission but are typically a few hundred meters with some extreme accuracy requirements

as low as a few meters. The accurate pointing of space-based antennas, optical sensors, and weapons is becoming an increasingly more difficult problem. The acceptable pointing and figure control errors are decreasing rapidly at the same time that the control problem becomes more difficult due to increased spacecraft flexibility and on-board disturbances (e.g., those generated by laser devices).

The testing of control systems for large, flexible structures will require emphasis in the coming years. Both ground testing and testing in space are needed to verify theory and establish performance limits. Orbital testing is important in regard to gravity effects and air-damping. Also, accelerated development of the actuators and sensors for future large space structures control systems is needed. For example, alignment sensors (such as laser devices) capable of measurements in the submicron range will be required.

NAVIGATION/GUIDANCE AND CONTROL

Desired Advances

- * Attitude control: accuracy--0.2 microradians
stability--0.005 microradians
- * Figure control: antennas--0.01 wavelengths
- * Navigation: accuracy--10 feet
- * Life: greater than 7 years
- * Autonomy

Technology Needs

Incremental Gain

- * Attitude control and pointing
- * Satellite guidance and navigation
- * Improved gyros
- * Improved control moment gyros

Potential for Large Gain

- * Figure control of large, flexible structures
- * Active damping/stiffness control

Man in Space

The cost of replacing a satellite when a malfunction occurs or when the solar array or batteries expire could lead to a requirement for repair, maintenance, and construction of orbiting space hardware as the cost of space systems and the cost of transportation of space systems to orbit increases.

For satellites in low earth orbit, and small enough to fit in the cargo bay of the shuttle, such service will probably begin by employing extendable arms and a retrieval vehicle from the shuttle. A current concept is the Teleoperator Maneuvering System (TMS) capable of retrieving satellites within one-half mile of the shuttle. The TMS will have the capability to rendezvous and dock with equipped spacecraft, bring it to the shuttle for repair, and return it to orbit after service.

For larger space structures, advanced flexible space suits will be needed to permit men to leave the shuttle and work effectively on the structure. This may start with "cherry picker" arrangements out of the shuttle, but will eventually evolve into vehicles capable of transporting men and equipment to a space structure from the shuttle and return. Manned operations in proximity with unmanned vehicles will require a number of fundamental developments for microlevel thrusters and in the guidance and control area.

The role of military man in space is presently under intense scrutiny as space station concepts are studied. There appears little doubt, however, that man's presence in space will expand. Remedies to motion sickness and other physiological disorders are required. Quick ingress/egress suits for extra vehicular activities (EVA) must be developed to make them less cumbersome and to reduce the long preparation times presently required. As EVA missions expand to assembly, fabrication, repair, and refurbishment of equipment and structures on orbit, lighter, smaller, and more responsive local space transport systems will be required. Some of the functions of man in space and the improved capability needed are listed in the following table.

MAN IN SPACE		
In-Space Operations	Capabilities Needed	Improving Man's Capability
<ul style="list-style-type: none"> • Low-Orbit Recovery of Some Low-Altitude Orbiters • Servicing of Low-Orbit Spacecraft <ul style="list-style-type: none"> – Replacement of Expended Parts, e.g., Batteries, Amplifiers, Solar Arrays – Refilling of Fuel Tanks – Exchange Payloads • Military Operations 	<ul style="list-style-type: none"> • Means of Despinning Some Satellites • Means of Restowing Deployed Structures • Means of Removing and Replacing Spacecraft Parts • Means of Transporting and Transferring Propellants 	<ul style="list-style-type: none"> • Physiological <ul style="list-style-type: none"> – Remedy for Motion Sickness – Hypervolemia, Calcium Loss • Habitat <ul style="list-style-type: none"> – Lightweight Space Suit (e.g., 8 psi) – Improved Life Support – Long-Life Radiation Protection – Lightweight • Tools and Training for Astronauts

The technology challenges in conjunction with direct or teleoperator tasks involve still unsolved physiological problems, new and (later) closed ecology systems, and a better understanding of man-machine interfaces and limitations. The safety problems of working in space are formidable, and each new step will require a thorough test program before it is undertaken.

MAN IN SPACE

Desired Advances

- * Remedies for motion sickness, hypervolemia, calcium loss
- * Suits--8 psi, quick ingress/egress
- * Life support--1 year; radiation protection
- * Smaller, lighter transport

Technology Needs

Incremental Gain

- * Physiological
- * Lightweight extra-vehicular activity suit
- * Life-support equipment
- * Life-support technology
- * Tools for man in space
- * Man/machines working in space

Potential for Large Gain

- * Local transport in space

Survivability

Almost all current spacecraft are designed to afford some protection to the mission if there is an on-board electronic failure or in the event the ground control center and system becomes disabled for a significant period of time. The most commonly used technique is an automatic maneuver into a "safe-hold" attitude and a shutdown of all nonessential functions to conserve power. Recovery involves ground diagnosis of the problem, corrective action, and reestablishment of control system operation and of the desired operational attitude. During such a period mission data are lost, sometimes for a considerable period.

The on-going revolution in the development of microelectronic devices promises future capability for the development of highly sophisticated and capable spacecraft computers rivaling today's ground super computers. These devices, along with the application of artificial intelligence techniques, could lead to the design of highly autonomous spacecraft capable of diagnosing and correcting on-board failures automatically and able to perform their missions in space for long periods of time independent of communications and control from the ground.

OGR.

The benefits of such developments apply to both civil and military users. On the civil side, autonomous spacecraft will ensure continuity of data with a low probability of major interruption, as well as the opportunity to significantly reduce costs associated with labor intensive ground operations and control centers. On the military side, the ability of a spacecraft to conduct its mission in spite of serious disruptions on the ground is obvious.

Autonomy has become a major issue for future spacecraft and a 10-step autonomy chart has been defined by the Jet Propulsion Laboratory in a study for USAF to chart progress.* Autonomy level 10 assumes complete ground disassociation from functions such as target selection and payload data processing. Today's spacecraft operate between levels 1 and 3, and the most sophisticated vehicles approach level 5.

Radiation hardening of spacecraft is mandatory for military space systems but civilian spacecraft will benefit from the development of the technology to permit radiation resistant systems because they will be more resistant to failure or upset caused by natural radiation in the Van Allen belts. Current spacecraft are designed to stay well below or above the maximum natural radiation intensity to avoid outright failure due to cumulative dose. However, during periods of

* United States Air Force Systems Command, Headquarters, Space Division. Goals for Air Force Autonomous Spacecraft. Prepared by Jet Propulsion Laboratory. March 31, 1981. USAF Report SD-TR-81-72. JPL Report 7030-1, Issue 1.

increases in natural particle populations, spacecraft can be and are affected by isolated "hits" in logic or memory circuitry. As microelectronic technology advances, chips will be produced with more and more components on each device. Systems of the future employing these devices must consider the necessity for using radiation-resistant semiconductors, or employing redundancy and majority voting circuitry.

VII.

Recommendations

The preceding sections outline the many opportunities for the technology investment that is critical if the U.S. leadership in space is to be maintained during the next century. The similarity in the needs for research and advanced technology development for civil, commercial and the military users of space, spacecraft manufacturers, and in-house NASA programs became apparent during the course of the study.

The following recommendations emerged from projections for the future use of the space environment as described by the Panel on the Uses of Space, the needs for advanced technology to support spacecraft design and construction as developed by the Panel on Spacecraft, the compilation and prioritization of these needs by the Panel on Technology and examination of the DoD and NASA Space R&T models and other briefing information. The first five recommendations are institutional in character and were developed in plenary session at the conclusion of the workshop on the basis of what had been learned during review of the existing program. The final 13 recommendations regard specific technologies and represent a consensus of views based on the best judgments of the workshop participants.

1. NASA should establish the level of resources (funds, manpower, and facilities) to be allocated to advanced space research and technology development for the next decade and protect these resources from the short term requirements of NASA's major operational programs.

NASA was the leading force in developing technology for application satellites and in recent years has developed the shuttle, which has become the nation's primary launch system. Development of the nation's capability to explore and operate in the space environment has dominated the NASA effort. However, during the past 15 years, the effort NASA has been able to devote to research and advanced technology development (predominantly the OAST Space R&T program) has shrunk from 5 percent to 2 percent of the overall NASA R&D budget, as the funding needs of the large development projects dominated the

agency's efforts. While NASA has carried out a number of excellent advanced technology development programs, the 30/20 GHz technology development program, for example, the spacecraft manufacturers and the civil, commercial, and military users of space have many technology needs that have not been addressed adequately. The U.S. spacecraft manufacturers and the users of space are convinced there will be a dynamic growth of satellite applications through the 1990s, and the workshop participants perceived a potentially important, currently unfilled role in the development of technology for applications spacecraft. There is a need for leadership to establish a program in research and long-term space technology development to overcome the current deficiencies, and NASA is the appropriate agency to provide this national focus. It has the technical personnel and facilities necessary to develop a "critical mass" of capability and a continuity of effort.

Engineering development is a critical element of high-technology work, and much of NASA's program activity has been devoted to finding solutions to near-term mission problems. Because of the urgency attached to such problems, OAST has been called upon to assist in finding solutions. This is appropriate when such work represents the culmination of longer-term development activities approaching readiness for mission applications. However, to the extent that these actually are developmental problem-solving tasks they represent a dilution of the long-term R&T effort. Such problems are real and must be solved, and the expertise that exists in NASA's research centers and OAST's R&T funds are often needed to solve them. But such work should be secondary to the OAST's principal task of conducting research to provide the technology base for future missions. This work needs to be protected. The interruption of research, sometimes permanently, is not only deleterious to the work immediately affected, but also destroys overall program continuity and OAST's ability to attract and hold the most capable research personnel. OAST has not been able to commit resources to long-term research objectives and technology advances in a number of instances. Many problems that confront spacecraft designers today received attention from OAST researchers in the past, but work was started and stopped because of lack of support. Examples include limited orbital transfer capability, lack of a long-life cryogenic cooler, lack of a practical space suit, and inability to process earth observation data in a timely manner.

In balance, OAST's program should be biased towards fundamental generic research and technology development for the long term, although some systems work is necessary for OAST to properly frame its technology program and some proof-of-concept testing utilizing ground facilities, aircraft and space flight is deemed essential to meet some research objectives.

To satisfy the basic research needs of the spacecraft manufacturing industry, it is recommended that NASA dedicate a portion of its resources, insulated from major program funding problems, to

continuing support of long-range space technology development and structure a research and advanced technology program that consists of both incremental technology development and high-potential, long-term breakthrough elements.

2. NASA should expand the charter of its space technology advisory committees, charging industry and university members with the responsibility of helping NASA to plan a technology program that is responsive to the needs of the broader space community and not just to NASA's in-house needs.

R&T Program Planning

The strength of NASA as a high-technology agency has been built both upon the resources within its research centers and upon its productive interaction with the scientific and technical communities of U.S. industry and academe. However, in the development of space technology NASA has drawn upon these communities almost exclusively as contractors/customers. After examining the NASA program and the interface with these communities, the workshop participants discerned a lack of involvement by industry and universities in helping to plan the NASA space R&T program.

OAST's R&T program planning would profit from increased external participation; both industry and academe should be involved in developing a time-phased program plan that would be reviewed and evaluated by an independent peer review process. Such a plan should encompass the requirements of NASA, DoD, users in the civil and commercial sector, and spacecraft manufacturers.

Another step in improving coordination between NASA and industry's space technology programs could be accomplished by involving NASA OAST in spacecraft manufacturers' independent research and development (I&D) programs.

NASA/Academe Relationship

Industry, NASA, and the nation require a strong academic engineering community. Also, basic research accomplished in the academic community, under contract, has been productive in the past. Presently, relatively few schools of engineering are addressing the unique challenges present in spacecraft technology and space transportation systems in either the courses of study offered or in research undertaken. Engineers trained in the space disciplines will be needed in increasing numbers and faculties motivated to focus on space technologies can be instrumental in assuring that students are adequately prepared. OAST should take steps to improve working relationships with universities in disciplines related to space engineering.

There are well-established OAST/university programs in aeronautics under which centers with specialization in some areas, such as computa-

tional fluid dynamics, are identified and supported by NASA. The faculty and graduate students in such centers can make critical contributions to the NASA R&T development programs, and it would be beneficial if such centers were established in the field of space technology. Other desirable facets of these OAST/university programs are:

- o Sabbatical leave for faculty to industry with NASA support
- o NASA personnel taking sabbatical leave to universities
- o Faculty on sabbatical leave to NASA centers

3. NASA/DoD cooperation in space R&T should grow.

Although coordination of R&T programs is difficult, the value of technology exchange and joint endeavors justifies the effort to make them happen. It is apparent that NASA's R&T program could serve technology needs of the military space effort. By broadening the STIG charter, OAST and the Air Force Systems Command have established a mechanism for cooperative, cost-effective research, development, and evaluation of new and emerging technologies for future space systems of NASA and the Air Force. It is too early to judge how effective this new mechanism will be--its success depends on interest and support from the top management of NASA and the Air Force. Demonstration of this interest and commitment by a policy statement by high-level DoD and NASA officials is highly desirable. Also, it would enhance the STIG mechanism for NASA representatives to attend Air Force Laboratory Technology Reviews to stimulate interaction at intermediate levels of management.

Although civil and military advanced research needs in space technology are very similar, specific performance requirements and priorities can differ. It is unreasonable to expect that all such research be conducted by NASA, and there should be a healthy program in the DoD directed towards specific problems and priorities. However, NASA must maintain the key responsibility for the collection and dissemination of unclassified research and development results to the civil community. This focal point role would be analogous to the one NASA now plays with respect to the aeronautical community in this country.

4. NASA should develop centers of technological excellence.

A center of excellence is defined as a NASA-wide activity housed at a field center or supported at a university with responsibilities to the space community at large. These centers might focus on areas such as on-orbit propulsion, large space structures, materials for space use, or on systems science, e.g. on systems design integration, bus interface standards, degrees of standardization for systems and orbits, modularization, or cost-benefit systems design issues. For such a center, program continuity must be assured to undertake

long-range programs appropriate to a federal laboratory, to provide career development, to aggregate the cohesive group of professional skills necessary to maintain a scientific critical mass, to develop the facilities required for advanced research, and to create the institutional prestige that attracts top talent. OAST should develop centers of excellence where expert knowledge in selected disciplinary areas will reside and be available to all.

Establishing centers of excellence should be a one-at-a-time controlled operation--not a wholesale implementation. The development of the program for such a center should be an interactive process involving the best experts from industry, academe, and government.

Because of the importance the workshop attaches to establishing centers of excellence and the care required in implementing them, a special report on the subject has been prepared and is contained in Appendix D.

5. NASA should provide access to space for experimental purposes as a natural extension of national aerospace facilities.

An important function of NASA is the acquisition and management of unique national facilities. The use of space will allow testing that is not possible by any other means. As a consequence, NASA should continue its efforts to use space for conducting research and technology development. The workshop participants endorse OAST's current undertakings to utilize the shuttle orbiter as a test facility for experiments; the Shuttle Pallet Satellite (SPAS), scheduled for flight in the shuttle in 1983 that will accommodate a variety of experiments, and the Long Duration Exposure Facility (LDEF), scheduled for space flight in 1984. OAST from these and other undertakings should systematically determine the usefulness and specifications for a more permanent test facility in space. Many different kinds of experiments are envisioned. The common denominator will be the real space environment--zero-g, high vacuum, and radiation effects.

One can envision a facility in space that has basic services available, i.e. instrumentation, sensors for measuring behavior, computers, data acquisition systems, and other housekeeping items.

An example of an experiment of high current interest that would benefit from such a facility is the investigation of large flexible structures in space.

Research and Technology Development

In the following discussion of needed technological advances it is recognized that some of the research and technology development described is being conducted by NASA to some degree and it is recommended that NASA restructure its program and augment it to stress these technologies.

1. Cost of using space. Escalating cost of the manufacture and testing of payloads, spacecraft, and transportation to orbit is the single most critical barrier to the use of space, especially to the commercial sector. These costs permeated the panels' discussions of technology needs, and it is recommended that OAST embark on programs that would lead to reductions in cost in all aspects of space technology. Rather than the usual production engineering approach of substituting materials or loosening tolerances where applicable, new concepts in designing the various systems should be sought that might lead to simplification and, thus, lower costs.
2. On-orbit propulsion. Little has been done to advance the technology of chemical propulsion since development of the space shuttle main engine. Heavy payloads and required spacecraft maneuverability will demand additional technology and greater efficiencies in propellants and engines. The cryogenic high-pressure LOX-Hydrogen and LOX-Hydrocarbon rocket engine is probably the single most important area for long-term work in propulsion. Advanced, high-specific-impulse propulsion systems for station keeping and orbital transfer vehicles will be required; optimal systems are not yet available. Participants also emphasized the need for development of chemical laser-stimulated propellants, plasma drive systems, and electric propulsion in addition to conventional propulsion systems.
3. Technology enhancement for large space structures. Large structures require long-term dimensional stability and resistance to distortion. Innovative design approaches and technological advances are needed to meet the challenges of construction, deployment, and maintenance of future space structures such as large antennas, large-precision optics, and platforms/stations. Key areas are the composition and erection of main structural elements, stiffness, thermal control and protection, heat pipe and coolant distribution improvements, lubricant development, inflatable structure application, and simulation testing. It is recommended that NASA/OAST develop the knowledge base for control of the geometry and orientation of large orbiting space structures.
4. Research on materials for space use. It is recommended that OAST develop an appropriate data base for characterizing the performance of materials in the space environment, especially

regarding temperature, out gassing, contamination, erosion, plasma effects, atmospheric density, and solar and nuclear radiation.

5. Architecture for organizing and disseminating data. There is a critical need for focused and innovative approaches to reduce the time and costs involved in obtaining data from space in formats usable by the civil, commercial, and military sectors. On-board data selection, storage, and reduction as well as orbiting and consolidated ground data facilities are already receiving research attention within NASA. The state of the technology does not appear to be the problem, but this area continues to be the principal inhibitor to commercial exploitation of information from various space sensing efforts and data management. It is recommended that NASA's R&T effort in this area be directed to determining the most efficient balance between on-board and ground data processing, means for providing radiation hardening for digital microelectronic devices for effective on-board processing, and providing the technology for very high speed integrated circuit technology, laser recording, acoustic-optical processing, fault tolerance and error detection and correction techniques.

Ground data processing is becoming a major cost item in space operations and it is recommended that NASA emphasize interrelated research activities, utilization of physical phenomena at the molecular level, the engineering of processing hardware, and software engineering technology in its OAST R&T program. In addition, the following computer science technologies will dominate applications for the future and should be included: user languages for direct design specification to code translation, computer security, expert systems (data bases), decision aids, artificial intelligence, and voice data entry.

It is also recommended that OAST emphasize R&T to improve the data systems architecture required to allow rapid, frequent, and cost-efficient processing of global remote-sensed data.

6. Sensors/payloads technology. Rapid increases are foreseen in utilization of space-based sensors for detection, identification and tracking of earth, atmospheric, and space targets--using both optical and microwave techniques. The anticipated military requirements in electro-optical sensitivity and accuracy will lead to a need for very large, lightweight optics and mosaic focal planes of millions of detectors as well as very large radars. Sensors for commercial and scientific application payloads require improved spectral and spatial resolution and the ability to make self-determinations of when data should be taken. The workshop participants view the following areas as amenable to quantum jump improvements: microwave sensing (both passive and active), visual, infrared, laser, and particle sensors.

7. Communications technology. This area, while related to data processing and payload categories, is important enough to merit special mention. Military requirements for privacy and information content are moving carrier frequency requirements to possibly above 100 gigahertz and assorted very large bandwidths to handle laser-communicator capabilities. The same requirements drive improvements in antenna designs and figure maintenance. Earth resource and environmental needs include low noise receivers, high power linear amplifiers, signal processors, and more efficient and intelligent data-compression techniques. Commercial applications press for antennas that are large and agile.
8. Power systems technology. Spacecraft power systems include power generation, regulation, distribution, and energy storage. By the year 2000, civil needs will be four- to fivefold present requirements and DoD needs will be in the megawatt range. Peak-to-average power ratios for missions such as space radar will be as high as 20:1. Longer life and reduced weight, along with energy storage, will be driving needs.

Development is essential in batteries, solar arrays and solar cells, nuclear power systems, and high-voltage distribution.
9. Environmental control. One side of this problem concerns contamination of optical and other sensors and environmental monitors from propellant effluents, material out- and off gassing, and particulates carried within the cargo bay. On the other hand, the radiation environment poses problems of spacecraft charging and degradation of microelectronic components that must be addressed.
10. Thermal control. Spacecraft trends toward longer life, higher heat loads and fluxes, stored cryogenic propellants, increased use of infrared sensors, closer dimensional control, radiation and laser vulnerability, and the future involvement of man in operations and refurbishment contribute to new requirements for thermal control. Analytical processes are needed to define and evaluate thermal control designs. New concepts and devices are called for including advances in low-temperature heat pipes, two-phase thermal management systems (pump assisted heat pipe or vapor chamber), lightweight flexible fluid lines with zero leak disconnect capability, long-life low-temperature refrigerators, lightweight radiators, high-flux laser mirror cooling, and cryogenic propellant storage and transfer systems.
11. Navigation, guidance and control. This area encompasses technology for satellite stability, pointing, maneuvering, attitude determination and control, navigation, and the devices needed to provide these functions for future spacecraft. The

need for accurate autonomous navigation and attitude and figure control for large flexible structures is expected to demand these developments. Accurate pointing of space-based antennas and weapons requires on-board knowledge of the satellite position--knowledge currently made available from the ground.

12. Support of man in space. The capability of repairing, maintaining, and constructing orbiting space hardware will require improved life support systems and flexible space suits with rapid ingress/egress to permit man to leave the shuttle and work effectively. Small, responsive space transportation systems with microlevel thrusters will be required, along with manual and "tele-" tools. An understanding of and remedy for motion or space sickness and other physiological disorders are needed as well.
13. Survivability. Autonomy and radiation hardening are the principal issues. Most current spacecraft afford some protection in the event of an on-board electronic failure or loss of ground control. Sophisticated spacecraft computers, comparable to today's super computers, along with the application of artificial intelligence techniques could lead to highly autonomous spacecraft capable of diagnosing and correcting on-board failures and of performing long missions in space independent of control from the ground. Radiation hardening of spacecraft is mandatory for military space systems, and civilian spacecraft will benefit from the technology because they will be more resistant to failure caused by natural radiation. As microelectronic technology advances, chips will be produced with more and more components. Such highly integrated circuitry can be more susceptible to radiation induced phenomena. Systems of the future employing these devices should consider the necessity for using radiation-resistant semiconductors or employing redundancy and majority voting circuitry.

OGR.

VIII.

Appendixes

Appendix A

OVERVIEW OF SATELLITE SYSTEM TECHNOLOGY

HISTORICAL BACKGROUND

Sidney Metzger

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OVERVIEW OF SATELLITE SYSTEM TECHNOLOGY

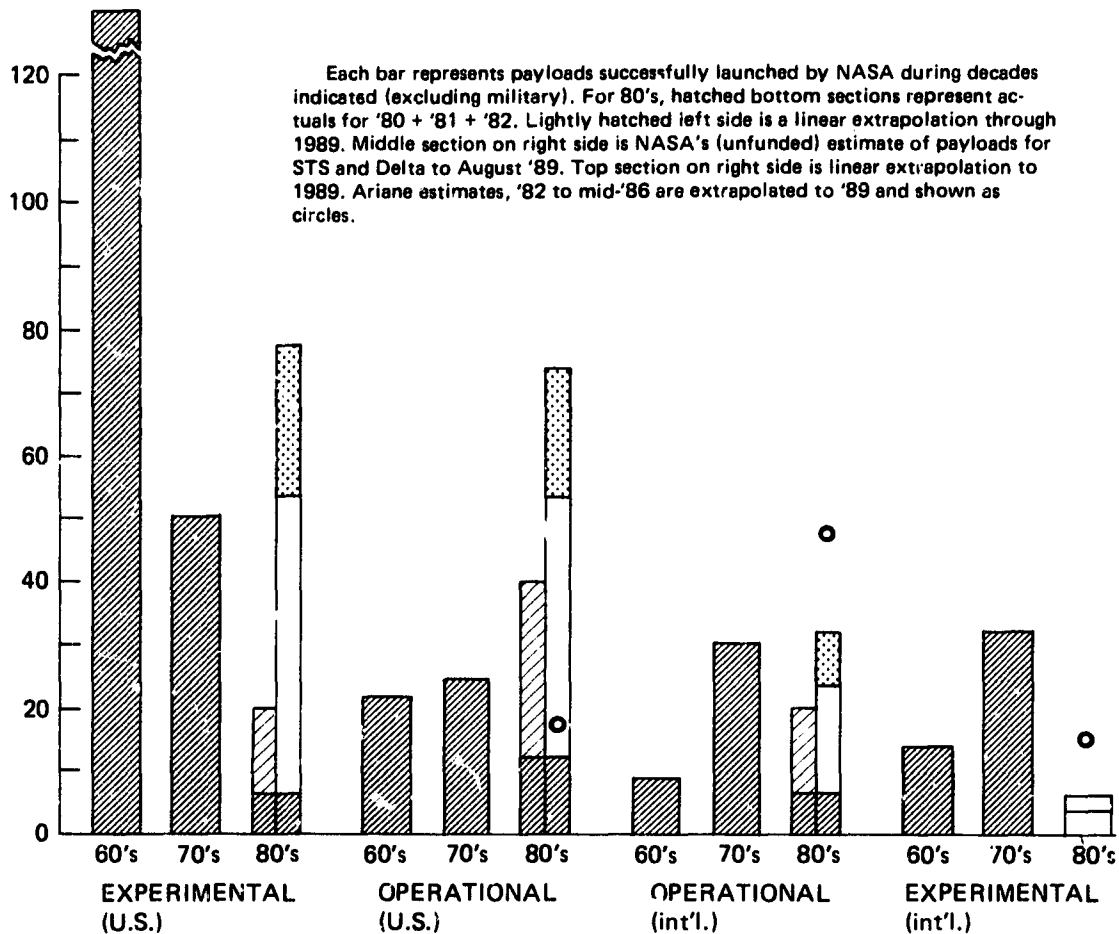
HISTORICAL BACKGROUND

The Beginning of the Decade of the 1960s

The NACA was converted into NASA on October 1, 1958, one year after the launch of Sputnik I (October 4, 1957). The early exploratory satellite period 1958-59 consisted of eight successful launches, followed by the explosive growth of the 1960s, with about 150 payloads successfully launched (excluding military launches). These included suborbital and orbital, manned and unmanned spacecraft and test vehicles of every description. The early spacecraft were test platforms for the components, techniques, and devices common to all satellites: attitude control, solar cells and storage battery power systems, thermal design concepts, structures, telemetry, antennas, and space propagation. The remarkable successes of these experimental flights laid the groundwork for operational space systems, so that within the same decade of the 1960s, Intelsat's commercial communication satellites were launched (nine satellites in all, including the Intelsat I, II, and III series). By the end of that decade, satellite communications were a major means of global telecommunications. Similarly, the weather satellites were in full operational use during the decade. It is significant to note that most of the technology used in both the communications and the weather satellites had been developed by NASA, in-house and/or by its contractors. This point is emphasized because it no longer held true in the next decade. The Intelsat and operational weather satellites were not included in the figure of 153 payloads listed for "experimental U.S. use," but the following chart shows the successful payloads in those categories ("operational U.S." for weather satellites and "operational international" for Intelsat and Skynet launches).

The European nations were determined to participate in this exciting new field and to achieve this goal in three different ways. They were members of Intelsat and therefore were aware of the status of its satellite designs and its R&D program, as well as being able to compete for Intelsat's R&D projects. In addition, they were members of the European Space Research Organization (ESRO) as active participants,

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Successful Satellite Launches

and, finally, they each had their own national space program. As a result, 14 international payloads were launched by NASA on a cooperative or reimbursable basis for Canada (3), United Kingdom (3), France (1), Italy (2), Germany (1), and ESRO (4).

These are also shown on the chart as "experimental-international."

The Decade of the 1970s

Two major events occurred in this decade that had a profound effect on long-range satellite technology in general and communications satellite technology in particular. This was the decade of the shuttle development, and almost all other NASA programs were subordinated to it. The result is strikingly seen on the chart, showing a precipitous drop in NASA's experimental payloads from the 153 of the 1960s to one-third this amount, or 50. While this decrease by a factor of three took place, NASA's launch of experimental payloads for other countries increased from 14 to 32 (2.3 times).

Comparing the number of satellites launched in one decade with those launched in the next decade, even with both in the same category, does not give a complete picture of their relative capabilities since the size and complexity of the satellites are not considered. However, comparing the relative numbers of two groups, "U.S." and "Int'l." in the same category, "operational," and in the same decade, provides a more meaningful estimate. For example, operational U.S. satellites (weather and domestic communications) in the 1960s were 22 vs. 8 for "Int'l," a ratio of 2.75 greater for the U.S., but by the 1970s the corresponding figures were 25 vs. 30, a ratio of only 0.83. Similarly, in experimental satellites for the 1960s, the "U.S." vs. "Int'l" satellites were 150 to 14, a ratio of 10.7, but by the 1970s the corresponding figures were 50 to 32, a ratio of 1.6. The conclusion to be drawn from the chart is the greatly increased participation of the West Europeans and Canadians as compared to the U.S. in space programs. This relative increase is due not only to the increased activity of the others, but also to the decreased activity of the U.S. As discussed elsewhere in this report, the percentage of NASA's annual budget spent on Space R&T has decreased from 5 percent in the early 1960s to about 2 percent in fiscal year 1983.

The reduction in NASA experimental payloads was reflected in the technology of the communications satellites of the 1970s. Whereas the designs of the Intelsat I, II, and III satellites of the 1960s could all be directly traced to NASA developed technology, the Intelsat IV, IVA, and V of the 1970s incorporated a number of new features which originated in military or commercial developments. The concept of spinning a satellite around its minimum, rather than its maximum, moment of inertia was borrowed from a military satellite, "TACSAT," and improvements were made to refine its performance. The development of dual polarization antennas, high-efficiency solar cells, and nickel hydrogen storage batteries was accomplished by commercial communications satellite organizations. All of these were relatively straightforward engineering developments of known technology rather than the more forward-looking developments of the type that should be undertaken by NASA.

During the early 1970s, Thompson CSF (France) and Telefunken (Germany) initiated development of both medium-power 12-gigahertz traveling wave tubes (TWT) (10-, 20-, and 30-watt level) and also high-power tubes (200-to 500-watt level) for satellite direct broadcast use. NASA's role of stimulating such technology development for future use had been greatly reduced by the early 1970s by the cancellation of most of its communication satellite program. A 200-watt TWT and its associated power supply, for operation at 12GHz, was developed by NASA and successfully operated in orbit for over 3 years in the experimental Canadian CT3 satellite, launched in 1976. Consequently, during the second half of that decade, all commercial satellites using that band purchased tubes from France or Germany. They included U.S. systems--Satellite Business Systems, the TDRSS (for NASA's use), Western Union, GTE, Intelsat V, and also RCA's ANIK for Canadian use--as well as European communication satellite programs. A half dozen American companies have applied for permission to launch direct broadcast satellites. These designs are all based on using European high-power traveling wave tubes.

The justification for cutting off NASA funding for advanced development of communication satellite technology was that such R&D should be done by the commercial organizations. In theory, this seemed reasonable, but at that time (1974) Intelsat, the world's largest satellite user, had a gross income of about \$101 million per year, while the cost of NASA's ATS-6, their latest satellite for testing of new communication space technology, was about \$200 million, both figures in then-current dollars. Clearly, the extent of the commercial market couldn't support such a cost. All commercial communications satellites purchased since 1964 have followed Comsat's approach of employing a fixed price contract with incentives for life in orbit. Such an approach is clearly desirable from a business viewpoint but calls for a specification largely based on proven technology. This pressure for a conservative approach is emphasized by the very high cost of such satellites. The DOMSATS are costing \$35-\$50 million each, and Intelsat VI, contracted for in 1982, will cost about \$140 million for the satellite, exclusive of launch costs.

The Decade of the 1980s

During the 1970s, Europe concentrated on developing components and techniques, as shown by NASA's launching 32 of their experimental payloads (up from 14 in the 1960s). However, by the start of the 1980s, they had built up enough experience to undertake total satellite projects and are now competing with U.S. manufacturers. An award for the design and construction of the Arabsat satellites was received by Aerospatiale. In addition, European governments are designing, or already have under construction, the following satellites--the French SPOT for earth observation, Telecom for their domestic communications, TDF for direct-to-home TV satellite broadcast, and the joint French/Swedish Tele-X for Scandinavian communications. The Italians have built two Sirio satellites and are

designing a 20/30 gigahertz satellite for their domestic telecommunications and the Germans an L-Sat for direct-to-home TV broadcast over their country. The U.K. is designing UniSat for domestic communications service.

The Europeans have already built and launched 2 MARECS on Ariane rockets, the second of which suffered a launch failure. The first MARECS has some problems but is being used operationally by Inmarsat. The European Space Agency is now building the European Communications Satellite (ECS) for providing communication services to all of the West European countries.

This emphasis on construction of operational satellites appears to be slowing down their work on experimental satellites. Only three are now estimated to be launched by NASA, and this extrapolates to five for this decade. The Ariane schedule calls for launching 4 experimental European satellites up to mid 1985. In that year they will go to 2 launch pads permitting 10 launches per year instead of 5. If the fraction of possible launches allocated to scientific satellites remains constant, perhaps 15 scientific satellites might be launched in the decade.

The chart shows that the number of experimental U.S. satellites actually launched in 1980, 1981 and 1982 totals 6 and if extrapolated to the entire decade would rise to 20, compared to 50 in the 1970s. By contrast, NASA's STS manifests show a total of 53 (including the previous 6) to mid-1987, but it is emphasized that these payloads are not funded. If they were to continue through 1989 at the same rate, there would be a total of 77. If half of these materialize, the new figure of 38 would still be significantly less than the 50 of the 1970s. As mentioned previously, numbers alone are not sufficient to compare the relative capabilities of satellites launched in different decades, but are useful as a first approximation.

While for some users with certain types of payloads Ariane is more available than the shuttle, its technology is conventional, similar to the Atlas/Centaur used by the United States a decade ago. In questioning U.S. spacecraft users, the single most commonly requested improvement was a low-cost readily available launch vehicle. Successful development or possibly modification and reconfiguration of existing launch vehicles resulting in lower cost launches, would not only be desirable for U.S. users, but might also be more competitive in the international market. Such an approach, if developed, could also be copied by the foreign competition, but meanwhile the United States would have a lead until the others catch up.

Worldwide, Arianspace estimates about 210 satellites would be launched in the last five years of this decade. About 150 of them are targets for the company after subtracting U.S. civilian and military satellites incompatible with the rocket. Arianspace expects to launch about 50 or more and perhaps as many as 65, about 23-31 percent of the worldwide total. The remainder would be launched by the United States.

Arianspace believes that at an average of seven launches per year and an average cost of \$70 million per launch (many carrying two satellites) after 1985 European launch business works out to about \$2.5 billion.

On the satellite side, the prime contractor for Europe is British Aerospace. A spokesman for the Stevenage plant said in an interview that the company believed it could take at least 25 percent of the world satellite market. Using a more conservative estimate of 150 satellites to be launched by 1990, he felt the world market was about \$5 billion in satellites alone. The European share could thus be about \$1.25 billion. Other sources in Europe see the satellite share going as high as \$4 billion.

In a news item of July 12, 1982, in Aviation Week & Space Technology, Japan's National Space Development Agency was reported to be reevaluating its space policy that calls for domestic development of the H-1 launch vehicle for 1,200-pound payloads by 1982 and for 1,760-pound payloads by the mid-1990s. It states that the Japanese Telegraph and Telephone Corporation and National Broadcasting Company are preparing larger vehicles to launch 2,200 pounds (this corresponds to the present Atlas/Centaur class for the geosynchronous orbit). A decision on accelerated development of a higher-thrust H-1 vehicle on whether to allow foreign launch vehicles for Japanese spacecraft is expected by the end of 1982.

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Appendix B

MILITARY SPACE TECHNOLOGY

FORECAST AND NEEDS

Anders L. Ljungwe

PURPOSE FOR MILITARY SPACE TECHNOLOGY DEVELOPMENT

The purpose for developing military space technology is to establish the technology capabilities on which future military space systems may be based. The goal is to develop the technology that will allow the deployment of military space systems that will provide a favorable, strategic balance. 3R.

The development and demonstration of the appropriate space technology capabilities will provide the options for design, construction, and development of space systems with superior characteristics with respect to:

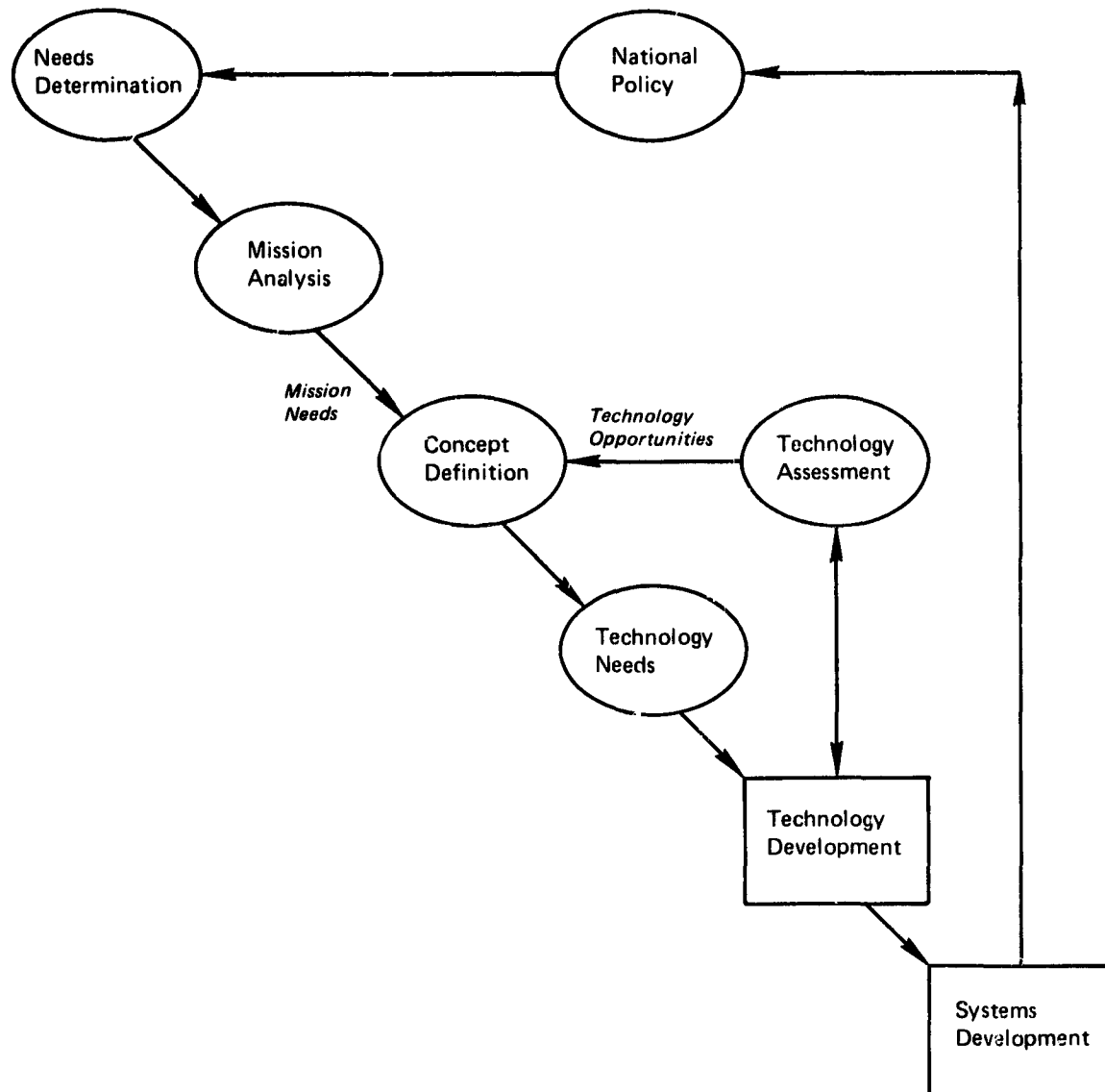
- o Performance
- o Survivability
- o Autonomy
- o Reliability
- o Maintainability
- o Affordability

THE MILITARY SPACE SYSTEM TECHNOLOGY MODEL (MSSTM)

For the past three years, the Deputy for Technology, U.S. Air Force Space Division has been assigned the task of identifying prioritized technology development goals and for stimulating the activities necessary for their attainment. A systematic approach has been developed for identifying future technology needs based on perceived mission requirements and technology opportunities. This planning process, illustrated by Figure 1, is an iterative one and is updated annually. The results are documented on an annual basis in the Military Space Systems Technology Model (MSSTM).

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The objectives to be achieved by use of the model are:

- o Establish a strong technology base program for advanced military space systems

- o Identify and rank major missions
 - DoD mission areas
 - User validation
- o Develop advanced system concepts
 - Evolution of current missions/systems
 - New technology opportunities
 - System context for technology focus
- o Identify key technology needs
 - System/mission need dates
 - System performance trade-offs
 - Technology assessment and projections
 - Technology priorities
 - Development road maps
 - Program investment strategy

The first edition of the MSSTM was published in January 1982, through the cooperative efforts of the Space Division, the operating commands, the Air Force Systems Command (AFSC) laboratories, and NASA. A second, expanded and enhanced edition of the MSSTM is planned for publication in December 1982.

The perceived space technology trends and needs summarized in this Appendix are based on the data presented in the first edition of the MSSTM.

CONCEPTS FOR FUTURE MILITARY SPACE MISSIONS

As illustrated by Figure 1, the future space technology needs are derived from mission requirements and technology opportunities. Figure 2 identifies mission areas and the more important military tasks and relates these tasks to the traditional space functional areas.

In order to identify the projected space technology needs, 27 representative space system concepts have been synthesized. These concepts, shown in Figure 3, have been selected so as to perform the mission and functional area needs identified earlier.

Figure 4 illustrates in a conceptual way the relationships between system drivers and the time-phased development and deployment of future systems. (Actual system drivers and systems have not been identified in order to maintain this document at an unclassified level.)

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SPACE FUNCTIONAL AREAS

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MILITARY TASKS

		SURVEILLANCE								FORCE APPLICATIONS						SPACE OPERATIONS
		AIR VEHICLE DETECTION AND TRACK	BALLISTIC MISSILE DETECTION AND TRACK	NUCLEAR DETONATION DETECTION AND LOCATION	SPACE VEHICLE DETECTION AND TRACK	SURFACE TARGET SURVEILLANCE/RECON	COMMUNICATIONS	NAVIGATION	ENVIRONMENTAL MONITORING	AIR VEHICLE DESTRUCTION	BALLISTIC MISSILE DESTRUCTION	SPACE VEHICLE DESTRUCTION	SURFACE TARGET DESTRUCTION	ELECTRONIC WARFARE	SPACE ACTIVITIES	SPACE LAUNCH
100	STRATEGIC WARFARE															
110	STRATEGIC OFFENSE															
	BALLISTIC MISSILE ACCURACY ENHANCEMENT															
	QUICK REACTION RECALLABLE WEAPON DELIVERY															
	SPACE-BASED WEAPON DELIVERY															
	DISCRIMINATING ATTACK CAPABILITY															
	SURVIVABLE SPACE-BASED TERRESTRIAL ATTACK															
120	STRATEGIC DEFENSE															
	WARNING OF BALLISTIC MISSILE ATTACK ON CONUS															
	DEFENSE OF CONUS FROM ATTACK BY BALLISTIC MISSILES															
	WARNING OF ATMOSPHERIC VEHICLE ATTACK ON CONUS															
	DEFENSE OF CONUS FROM ATTACK BY ATMOSPHERIC VEHICLE															
	WARNING OF SPACE-BASED WEAPON ATTACK ON CONUS															
	SPACE VEHICLE DETECTION AND TRACK															
	WARNING OF ATTACK ON U.S. SATELLITES															
	DESTRUCTION OF HOSTILE SPACE SYSTEMS															
140	STRATEGIC SUPPORT															
	SURVIVABLE LAUNCH															
200	TACTICAL WARFARE															
210	LAND WARFARE															
	SPACE-BASED TARGET DESIGNATION															
230	NAVAL WARFARE															
	WARNING OF ATMOSPHERIC VEHICLE ATTACK ON NAVAL TASK FORCE															
	DEFENSE OF NAVAL TASK FORCE FROM ATTACK BY ATMOSPHERIC VEHICLES															
250	SPACE WARFARE															
	DEFENSE OF U.S. SATELLITES															
	SPACE OPERATIONS															
300	INTELLIGENCE AND C3 PROGRAMS															
320	TACTICAL INTELLIGENCE AND RELATED ACTIVITIES															
	TACTICAL BALLISTIC MISSILE LAUNCH DETECTION AND TRACK															
	THEATER DEEP STRIKE TARGETING															
	TACTICAL AIR VEHICLE SURVEILLANCE AND TRACK															
330	STRATEGIC C3 PROGRAMS															
	DYNAMIC STRATEGIC FORCE CONSTRUCTION															
	STRATEGIC AIRCRAFT PENETRATION ENHANCEMENT															
	STRATEGIC AIRCRAFT FORCE RECONSTITUTION															
	SPACE-BASED NATIONAL COMMAND POST															
	COMMUNICATIONS FOR STRATEGIC FORCE MANAGEMENT															
340	THEATER AND TACTICAL C3 PROGRAMS															
	INTRATHEATER COMMUNICATIONS SUPPORT FOR C2															
370	ELECTRONIC WARFARE AND COUNTER C3I															
	SPACE-BASED GROUND RADAR JAMMER															
	SPACE-BASED COMMUNICATION JAMMER															

Performance needs for these tasks are evaluated

*Addition to DoD mission area list

FIGURE 2 Military Tasks/Space Functional Area Breakdown

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MILITARY TASKS

GR. 1

FUNCTIONAL AREA	MILITARY TASKS									
	1	2	3	4	5	6	7	8	9	10
SURVEILLANCE	1. AIRCRAFT TRACKING									
	2. AIRCRAFT IDENTIFICATION									
	3. AIRCRAFT CLASSIFICATION									
	4. AIRCRAFT POSITIONING									
	5. AIRCRAFT SCHEDULING									
	6. AIRCRAFT PRIORITY									
	7. AIRCRAFT STATUS									
	8. AIRCRAFT TRACKING									
	9. AIRCRAFT IDENTIFICATION									
	10. AIRCRAFT CLASSIFICATION									
COMMUNICATIONS	1. AIRCRAFT TRACKING									
	2. AIRCRAFT IDENTIFICATION									
	3. AIRCRAFT CLASSIFICATION									
	4. AIRCRAFT POSITIONING									
	5. AIRCRAFT SCHEDULING									
	6. AIRCRAFT PRIORITY									
	7. AIRCRAFT STATUS									
	8. AIRCRAFT TRACKING									
	9. AIRCRAFT IDENTIFICATION									
	10. AIRCRAFT CLASSIFICATION									
ENVIRONMENTAL MONITORING	1. AIRCRAFT TRACKING									
	2. AIRCRAFT IDENTIFICATION									
	3. AIRCRAFT CLASSIFICATION									
	4. AIRCRAFT POSITIONING									
	5. AIRCRAFT SCHEDULING									
	6. AIRCRAFT PRIORITY									
	7. AIRCRAFT STATUS									
	8. AIRCRAFT TRACKING									
	9. AIRCRAFT IDENTIFICATION									
	10. AIRCRAFT CLASSIFICATION									
SPACE OPERATIONS	1. AIRCRAFT TRACKING									
	2. AIRCRAFT IDENTIFICATION									
	3. AIRCRAFT CLASSIFICATION									
	4. AIRCRAFT POSITIONING									
	5. AIRCRAFT SCHEDULING									
	6. AIRCRAFT PRIORITY									
	7. AIRCRAFT STATUS									
	8. AIRCRAFT TRACKING									
	9. AIRCRAFT IDENTIFICATION									
	10. AIRCRAFT CLASSIFICATION									

SPACE FUNCTIONAL AREAS

FIGURE 3 Concepts for Future Military Space Systems

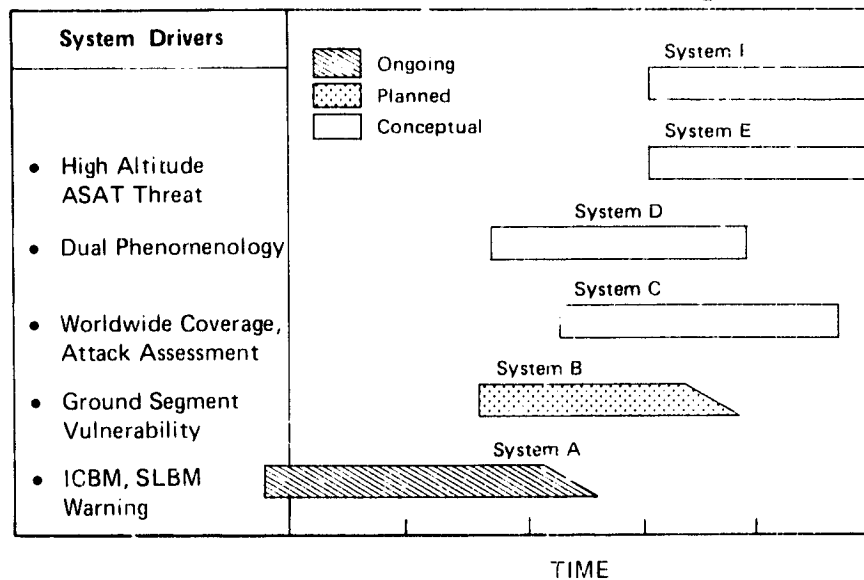


FIGURE 4 Ballistic Missile Surveillance and Warning

Possible time phasing of these programs is suggested, with new systems introduced to meet an emerging threat, a new performance requirement, or a logical follow-on or block change to a current system. The conceptual systems indicate options to meet a variety of possible future requirements. The program lines indicate dates for initial operation--the required technology base is to be available five years prior to initial operation in order for low-risk engineering development to proceed.

The 27 concepts have been selected as representative of a broad range of potential future space systems. Although it is doubtful that all of the 27 concepts will ever be implemented, it is believed that the technology needs derived from this family of concepts provide a good estimate of the future requirements in the key technology areas.

TECHNOLOGY FORECAST AND NEEDS

Projected space technology needs have been derived from preliminary designs for the 27 selected space concepts. These system definitions are based on system performance needs, the state of the art and estimates of the trends of applicable technologies, and assessments of the key technology trade-offs and payoffs. The resulting technology requirements are grouped into 14 disciplines listed as follows:

- | | |
|--|---|
| 1. Propulsion
Primary
Secondary
Satellite | 7. Navigation, Guidance and Control
Attitude
Orbit
Pointing accuracy and stability |
| 2. Power/Energy
Solar
Batteries
Fuel cells
Nuclear
Power distribution | 8. Information Processing
Signal processor
Computers/software
Circuitry
Hardening |
| 3. Materials | 9. Cryogenics/Thermal Control
Refrigerators
Thermostats
Heat pipes |
| 4. Structures | |
| 5. T/M and Communication
Antennas
Amplifiers and oscillators
RF characteristics | 10. Weapons
Directed energy |
| 6. Sensors
IR
Radar
Optical
Measurement | 11. Man In The System
Life support
Man/machine interface |
| | 12. Manufacturing |
| | 13. Survivability |
| | 14. Natural Environment
S/C charging
Weather
Van Allen belt |

The technology development goals for the early 1990s, which may yield significant payoffs in terms of system performance, survivability, autonomy, reliability, maintainability and/or affordability, are presented in Figures 5 through 8.

It should be noted that these goals are preliminary in nature and are expected to evolve with progress in system definition and the state of the art in the various technologies.

C - 2

TECHNOLOGY	SYSTEM PAYOFF
Propulsion	
Low-Thrust Chemical	Increased Payload Military Access to Space Large Structures, OTV Maneuver Capability
Heavy Lift Chemical	
Advanced Propulsion Systems	
Electric Propulsion	
Power	
Long-Life Batteries	Improved Specific Power Improved Survivability Increased System Capability Reduced Weight Enable Advanced Concepts
Advanced Power Processing	
High-Voltage Distribution	
Nuclear Reactors	
Materials	
Advanced Composites	Increased Stiffness Reduced Weights Survivability
Improved Material Capability	
Structures	
Large Deployable Antennas	Space Radars Space Weapons
Space-Based Fabrication, Assembly, Deployment	
Lightweight Optics	Military Access to Space
Hot Structures	

FIGURE 5 High Payoff Technologies (Part A)

Advances Sought by the Mid-1990s

- Launch Vehicles
 - High I_{sp} (~380 s (SL), >465 s (VAC))
 - High T/W
- Orbit Transfer Vehicles
 - High I_{sp} (~475 s Vacuum-Cryogenic)
(~330 s Vacuum-Storable)
- Satellite Propulsion
 - Chemical (I_{sp} ~300 s, Biprop or Augmented Hydrazine)
 - Electric (I_{sp} ~1500 s or More)
- Cryo-Storage and Transfer
 - Long Life (~3 yr)
- Environment
 - Reduced Contamination
 - Reduced Emittance

Potential Systems Benefits

- Space Transportation
 - Lower Cost, Faster Response, Greater Payloads
- On-Orbit Operations
 - Position and Attitude Management, Evasive Maneuvering, Construction and Deployment, Maintenance and Upgrade, Robotics

FIGURE 5a Propulsion

Advances Sought by the Mid-1990s

- Solar Power Systems
 - High Power (>35 kw, ~ 15 W/lb)
 - High Cell Efficiency ($\sim 22\%$ e.g., GaAs, MBG)
 - High Battery SP Energy (~ 20 W-hr/lb GEO, e.g., CPV NiH_2)
 - Long Life (>19 yr GEO)
 - High Radiation Resistance ($\sim 5 \times 10^{15}$ e/cm²)
- Nuclear Power Systems
 - High Power Reactor (>1 MW_e, 50 W/lb)
 - High Specific Power RTG (~ 5 W/lb)
 - Safety/Survivability
- Fuel Cells
 - High Power (~ 100 kw, 65 W/lb)
 - Long Life ($>3 \times 10^4$ hrs)
- Power Distribution
 - High Voltage AC (120 V, 10 kw, 100 W/lb)

Potential System Benefits

- Less Weight and Cost, More Life and Survivability
- Enables High Power/Energy Missions, e.g., OTV, Radar, Long-Term Life Support, HEL, ECM

FIGURE 5b Power and Energy

Advances Sought by the Mid-1990s

- Materials
 - High-Spec Stiffness (10^9 Inches, High E, Low ρ)
 - High-Thermal Def Resis High K_{trans} , Low α
 - High-Service Temp ($>700^\circ\text{K}$, e.g., cond-cure polyimides, Gr/Al, XiC/Ti, C-C)
 - High-Temp Superconductors ($\sim 18\text{K}$:Nb₃Sn)
 - Long Life in Space (~ 10 yrs)
 - Minimum Mass Deposition
- Structures
 - Light, Large Optics
 - Large Deployable Antennas (~ 100 m)
 - Integral Structure/TPS for Reentry
 - Innovative Space Structure Design/Assembly Techniques

Potential System Benefits

- Adv Sensors and Comm: Large Light Antennas and Optics, Easier PTG/STAB
- Lighter Launch Vehicles, Higher Impulse Engines, Relaxed Reentry, Greater Reusability, Lower Cost Access to Space
- Increased Operating Temp: Nozzles, Reentry, Reactors
- Lighter Spacecraft

FIGURE 5c Materials and Structures

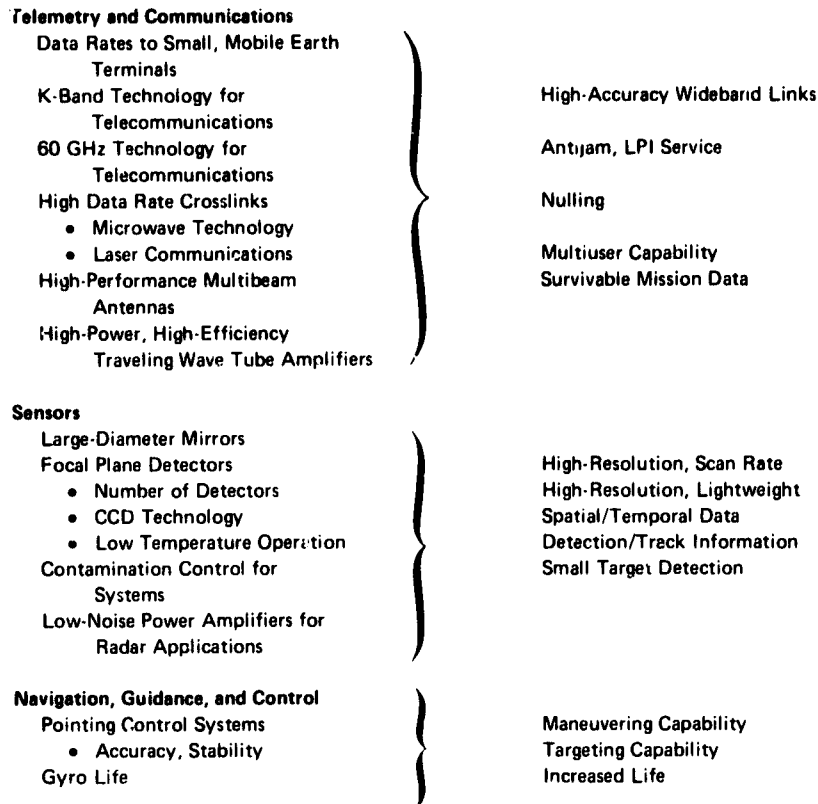


FIGURE 6 High Payoff Technologies (Part B)

Advances Sought by Mid-1990s

- Transmission Rates (per link)
 - μ Wave, GEO to Earth, Up to 5 gbps
 - Laser, GEO to GEO, Up to 5 gbps
- Solid-State Amplifiers
 - High Power, IMPATT: 15 W/60 GHz 8-Way Combiner
 - GaAs FET: 40 W/20 GHz 8-Way Combiner
 - Long Life (>10 yr)
- Lightweight, Dual Frequency, Deployable Antennas, 8 M, 44/20 GHz
- Onboard Signal Processing
 - Coding Gain (~ 7.5 dB for 10^{-6} BER)
 - Voice Bandwidth Compression (10 dB)
 - Throughput 5 gbps/Link

Potential System Benefits

- Higher Data Rates: Small Mobile User Terminals
- Improved ECM, LPI, Survivability

FIGURE 6a Communications

Advances Sought by the Mid-1990s

- Mosaic CCD Focal Planes (e.g., PV HCT)
 - Many Detectors $\sim 4\text{-}7 \times 10^6$
 - High Temp $\sim 120^\circ\text{K}$ MWIR, 40°K LWIR
- Lightweight Mirrors
- Tunable Filters, e.g., $2.5\text{-}5\ \mu\text{m}$, POL REJ $\sim 10^5$
- Cooling: Long Life (>5 yr), High Capacity
- Onboard Data Processing
 - Throughput: $>10^3$ MOPS, 3×10^3 Mbps
 - Memory: $\sim 10^4$ Mbits
 - Improved Algorithms
- Better Background and Target Models

Potential System Benefits

- Higher Resolution and Sensitivity Against Dimmer Targets
- Less Weight

FIGURE 6b Electro-optics

Advances Sought by Mid-1990s

- Better Resolution
 - Pulse Doppler: ~ 1 km, Velocity ~ 1 m/s,
Min Det Velocity: ~ 50 Knots
 - Syn Aperture: ~ 1 m (Target Identification)
 - Radiometer: ~ 4 m (e.g., $\Delta T \sim 2\text{K}$, 8-16 beams)
- RAD-Hard, Lightweight Solid-State T/R Modules
 - 3 GHz: ~ 30 W, NF ~ 1 dB
 - 1.2 or 3 GHz (~ 1 Watt; NF; ~ 2 dB; Wt/Element < 5 g)
 - 60 GHz: ~ 3 W, NF ~ 3 dB
- Onboard Data Processing:
 - Throughput: $>10^3$ MCOPS, $>10^3$ mbps
 - Memory: 10^3 mbits
- Large Antenna Deploy/Control
(~ 100 m DIA, $\sim \lambda/100$ Surface Tolerance)
- Better Clutter and Signature Models

Potential System Benefits

- Better Target Detection, Identification, Tracking
- Better Survivability; Longer Life
- Lower Weight and Costs

FIGURE 6c Radar

Advances Sought by the Mid-1990s

- Attitude Control
 - High Accuracy ($< 0.5\ \mu\text{rad}$)
 - Good Stability ($< 0.005\ \mu\text{rad}$)
 - Rapid Stability Rate ($< 2\ \mu\text{rad/s}$)
- Ephemeris
 - High Accuracy (~ 10 ft)
- Autonomy and Long Life (> 7 yr)

Potential System Benefits

- Control of Large Structures: Deployment, Figure, Pointing
- Precise Pointing of Sensors and Weapons
- On-Orbit Operations: Robotics, Rendezvous, and Docking
- Autonomous Operations

FIGURE 6d Navigation, Guidance and Control

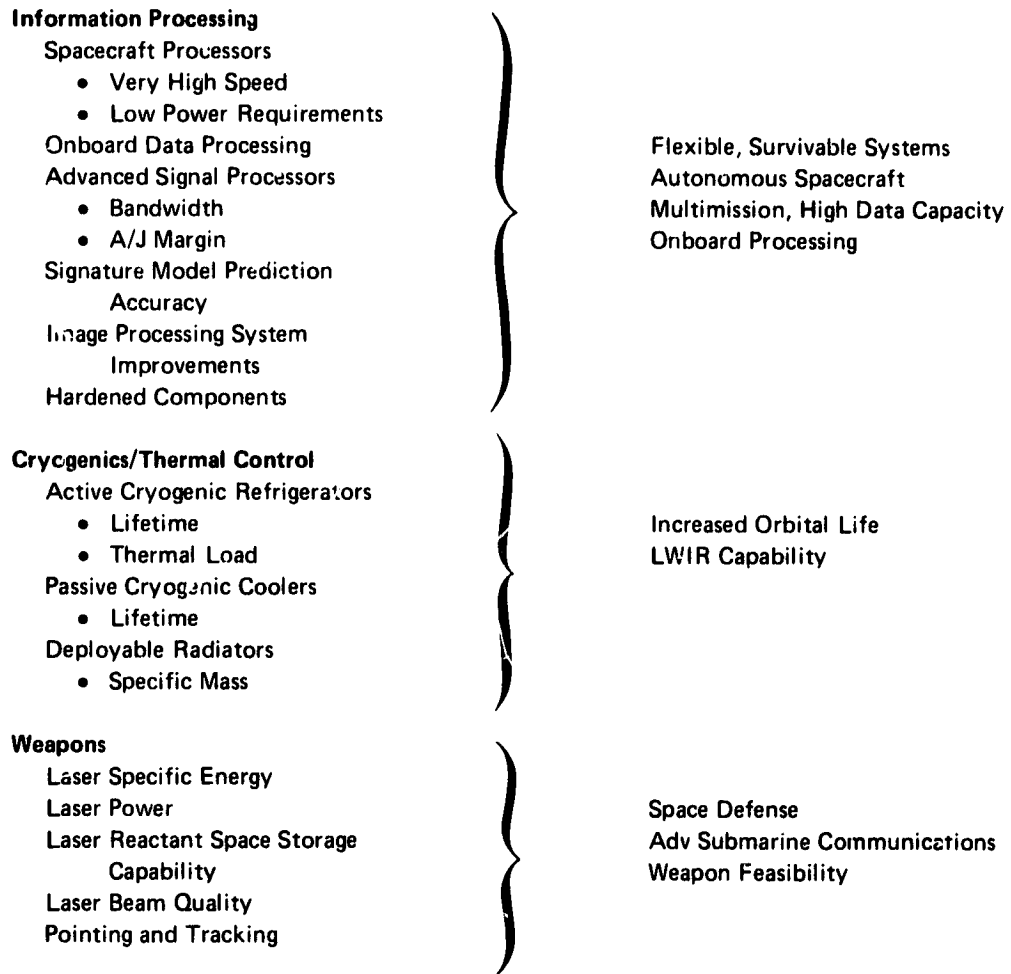


FIGURE 7 High Payoff Technologies (Part C)

Advances Sought by the Mid-1990s

- Overall Performance of Onboard Processors
 - High Data Rate (10^3 - 10^4 Mbps); High Throughput (10^2 - 10^3 MOPS)
 - High Capacity, Bulk Memory (10^3 - 10^4 Mbits, 0.5-2 μ s)
 - Endurable: RAD-Hard, Fault Tolerant/Autonomous
- Hardware: Hard VHSIC (e.g., ~ 50 ps, 1 μ m GaAs MESFET; 64 kbits chip)
Hard Mass Memory (e.g., bubble, MNOS)
- Software: Fault-Tolerant, Distributed Architecture
High Speed Algorithms (e.g., adv EO & RF sensors)

Potential System Benefits

- Adv Sensors and Comm: Large Mosaic Focal Planes ($>10^7$ elements); Better Resolution/Clutter Rejection; RT Event Recognition/Correlation to Small Users
- Endurability: Better ECCM, S/C Autonomy, Network Auto-Reconfiguration
- Large Structure and Optics Figure Control
- On-Orbit OPNS & Man-Machine I/F: Robotics, Smart Mobile Terminals, Fast Failure Analysis
- Auto-Programming, Fast Design/Test/Maintenance
- Less Weight and Power

FIGURE 7a Information Processing

Advances Sought by the Mid-1990s

- Refrigerators
 - Long Life (~ 10 yr)
 - Low Temp., Lightweight ($<10^\circ\text{K}$; 10% CARNOT Efficiency)
- Thermal Management
 - Variable Conductance Diode Heat Pipes (10 - 500°K)
 - Lightweight Radiators (1 - 2 kg/m 2)

Potential System Benefits

- Improved Cooling for High-Power Radars, Comm, Infrared Focal Planes, Nuclear Reactor Applications
- Cryo-Storage on Orbit

FIGURE 7b Thermal Control

Advances Sought by the Mid-1990s

- Physiological
 - Remedies for Motion Sickness, Hypervolemia, Calcium Loss in Zero-G
- Habitat
 - Lightweight EVA Suit (e.g., 8 psi)
 - Improved Life Support
 - Long-Life (~ 1 yr)
 - Radiation Protection
 - Lightweight

Potential System Benefits

- Lower Cost, Higher Reliability, Greater Flexibility in Manned Applications

FIGURE 8 Man in Space

PRIORITIZATION OF TECHNOLOGY NEEDS

Reaching the technology goals identified in Figures 5 through 8 would lead to future military space systems with substantially enhanced capabilities. However, the funds that could be expected to be available for technology development are limited, and it appears unlikely that all of these technology goals could be pursued. Thus, a prioritization of the technology goals is necessary. There are several approaches one may use for technology prioritization. The approach selected here is based on a prioritization of the mission areas and military tasks (Figure 2) (which can be accomplished based on published U.S. space policies and DoD mission rankings) and then propagating these priorities through the selected space concepts down to the individual space technologies. A high-priority technology would then have the following characteristics:

- o The accomplishment of the stated technology goal would lead to substantial improvements in concept capability and/or cost as compared to the investment required for reaching the goal.
- o The technology goal would substantially affect the capability and/or cost of several concepts.
- o The concepts affected by a prioritized technology provide primary support of high-priority missions.

The results of such a technology prioritization are presented as follows:

1. INFORMATION PROCESSING: Microelectronics and on-board processors
2. INFORMATION PROCESSING: Software and algorithms
3. PROPULSION: Launch vehicles and orbital transfer
4. PROPULSION: Propulsion for station keeping
5. STRUCTURES: Large antennas
6. COMMUNICATION: Solid state amplifiers
7. THERMAL CONTROL: Passive
8. SENSORS: Solid state T/R modules for radar
9. COMMUNICATIONS: Large, multibeam antennas
10. GUIDANCE, NAVIGATION, CONTROL: Autonomous attitude control
11. ELECTRIC POWER: Solar power (cells, batteries)
12. MATERIALS: Materials for space structures
13. COMMUNICATIONS: High transmission rates
14. SENSORS: Large antennas for radars
15. ELECTRIC: Solar power (power management)
16. SENSORS: Large, lightweight optics
17. SENSORS: Accurate phenomenology models
18. GUIDANCE, NAVIGATION, CONTROL: Autonomous navigation
19. GUIDANCE, NAVIGATION, CONTROL: Long life gyros
20. SENSORS: Electro-optical focal plane
21. PROPULSION: Contamination control
22. MAN-IN-SPACE: Physiology
23. MAN-IN-SPACE: Habitat
24. THERMAL CONTROL: Active cooling
25. WEAPONS: High energy laser devices
26. ELECTRIC POWER: Space based nuclear reactor

It should be recognized that, although this technology prioritization may be utilized as a guideline in formulating a long-term technology development program, the process involves many uncertainties and subjective judgments and, therefore, should not be the sole basis on which such a program is formulated.

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Appendix C

AFSC/NASA MEMORANDUM OF UNDERSTANDING

SPACE TECHNOLOGY INTERDEPENDENCY GROUP (STIG)

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AFSC/NASA MEMORANDUM OF UNDERSTANDING
SPACE TECHNOLOGY INTERDEPENDENCY GROUP (STIG)

1. GENERAL: The Space Technology Interdependency Group (STIG) is established to provide cooperative, cost-effective research, development, and evaluation of new and emerging technologies for space systems that are of interest to both the National Aeronautics and Space Administration (NASA) and the Air Force Systems Command (AFSC). The overall goal of the STIG is to provide oversight and guidance for joint space technology development programs that will culminate in cost-effective verification and/or validation on either NASA or AFSC space test vehicles. Individual NASA/AFSC technology areas and programs identified by the STIG as mutually beneficial will be tailored to achieve mutually agreed management and technical objectives. The STIG is a direct evolution from the AFSC/NASA Space Technology Interdependency Working Group jointly initiated in December 1973 to exchange status briefings on programs of mutual interest.

2. PURPOSE: This Memorandum of Understanding (MOU) establishes the relationships and responsibilities of the STIG. The STIG is charged with identifying candidate programs and encouraging joint AFSC/NASA dependent and interdependent technology programs and monitoring the status of these programs to help ensure successful implementation and completion.

3. DEFINITIONS: Joint programs between AFSC and NASA have various levels of dependency. The following two general definitions will be used in this MOU.

Interdependent Programs

An interdependent program is one that has some degree of overlap in stated AFSC and NASA program and/or technical goals. Interdependent programs include a subset of common technical objectives and an administrative means of communicating progress, though not always for formal instruments (such as Memorandum of Agreement). The overall success of interdependent programs is not conditional upon the performance of either agency, although some complimentary results beneficial to each are assumed to result. In this sense, inter-

dependent programs are not as tightly connected as dependent programs defined below.

Dependent Programs

Dependent programs are those that share a single set or subset of mutually constructed program goals, and the efforts and resources of both NASA and AFSC are crucial to the success of the program. Dependency implies formal agreements (MOAs), coordinated management, shared resources, and strong AFSC and NASA Headquarters support, all of which result in a more vigorously interconnected program.

4. MEMBERSHIP, RELATIONSHIP, AND RESPONSIBILITIES: The responsibility for management and administration of the Space Technology Interdependency Group is assigned jointly to HQ NASA/OAST and HQ AFSC/DL. The Cochairmen of the Group will be for AFSC the Assistant Director of Laboratories (HQ AFSC/DL) or his designee and for NASA the Deputy Associate Administrator of the Office of Aeronautics and Space Technology (NASA/OAST) or his designee.

R. 1

Each Cochairman will appoint at the Headquarters level (HQ NASA/OAST and HQ AFSC/DL) for membership in the Executive Committee of the STIG: (1) A Focal Point Manager for each technology area established by the Interdependency Group and (2) an Executive Cosecretary. Individual technology Focal Point Managers are responsible for technical and program guidance to field agencies for their technology area. The Executive Cosecretaries are responsible for planning, organizing, and documenting STIG meetings minutes, tracking action items, and accomplishing other administrative tasks as requested by the Cochairmen. Other technical and program management personnel may be added to the Committee by the Cochairmen as circumstances require.

5. OPERATIONS: The Cochairmen may convene STIG Executive Committee meetings at any time to address business appropriate to the STIG. General meetings of the STIG involving field agency participation will be convened at the call of the Executive Committee to receive and comment on the status of proposed and ongoing interdependent programs. Site locations for the general meetings will alternate between NASA and AFSC locations. Minutes of all STIG meetings will be generated by the Executive Cosecretaries and distributed after approval by the Cochairmen.

Technology disciplines areas (such as electronics, propulsion, power and environment, etc.) will be established as appropriate by the STIG. Technology areas are not fixed and will be reviewed by the Cochairmen periodically to ensure adequacy and appropriate coverage.

The interdependency process is a continuing process of assessment and requires continuous coordination by the Focal Point Managers at both HQ AFSC and HQ NASA. Specific MOAs between NASA and AFSC field organizations are encouraged for those interdependent programs

Appendix D

CENTERS OF EXCELLENCE

AND OAST'S

SPACE RESEARCH AND TECHNOLOGY PROGRAM

John H. McElroy

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I. INTRODUCTION

Research on new technology for space systems can serve multiple functions. Among them are institutional support as well as the more traditional role of advancing technology. The NASA/OAST Space Technology Program addresses both.

NASA faces the same problems that all high-technology, project-oriented organizations face: How can the skills of project personnel be kept current, and how can those people be usefully employed between projects? These are problems that can be ameliorated through the judicious use of applied research projects. Personnel, particularly in matrix engineering support organizations, can be employed on such research projects on either a full- or part-time basis. Presumably, the projects can hone skills and contribute to the applied research or development needs of the organization and NASA. While such a practice is entirely legitimate from an institutional management perspective, these activities must be considered training or useful gap-fillers--not systematic research and development aimed at producing significant advances in space technology. Truly significant results from such dispersed and sporadic activities will be inevitably sparse. Thus, while some fraction of OAST's resources may be devoted to organizational sustenance, they should come under a different scrutiny than would be employed for true advanced activities.

In the succeeding sections, no further attention will be paid to such efforts, and the focus will be exclusively on activities aimed at major advances in space technology. It is the prerogative of OAST management to determine the proper balance between the two categories of research activities; it is only necessary that the determination of that balance be by explicit decision and not by mere chance or the absence of consideration.

II. THE NEED FOR FOCUS

No research organization disputes the need for careful planning. Certainly, OAST management needs no convincing. Therefore, the following paragraphs are intended to be only a few general observa-

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tions relevant to the NASA and OAST environment, with special emphasis on the need and benefits of a sharp focusing of the program.

A. Dispersion and Program Resources

OAST does not presently, or even under the most optimistic budget assumptions, have the resources to carry out productive advanced research and development in a large number of disciplines. OAST must play a counterpoint to activities in industry and the Department of Defense in a relatively few carefully selected and coordinated areas if OAST's efforts are to be effective. The management of those activities must be carried out by people intensely knowledgeable about the work being carried out by their professional counterparts in the other sectors. Such a management will always be aware of exactly where a particular project fits in the total international environment that characterizes advanced technology. Their efforts must be professionally judged as a part of that overall milieu--and never only in terms of some local environment. When the above occurs, the efforts will be automatically focused on the genuine pressure points and gaps in understanding for a particular discipline.

B. Historical Perspective

There are no secrets to creating a favorable environment for research and development. Every working scientist and engineer knows the fundamentals and can probably quote the examples demonstrated by a number of famous institutions. When an American thinks of the development of radar, it is likely that MIT's magnificent Radiation Laboratory of World War II comes to mind. Early atomic physics research brings to mind the Cavendish Laboratory, led at various times by James Clerk Maxwell, Lord Rayleigh, J. J. Thomson, and Ernest Rutherford. A long list of such institutions is easy to prepare. The message is clear; productive work comes from outstanding leadership, adequate facilities, a dedicated and skilled professional staff, objectives that are evident to all, and--perhaps most importantly--institutional continuity that allows the above characteristics to evolve and flourish. It is the concept of a "Laboratory"--with all of its inherited intellectual ethos--that has led to advances in the past and will in the future.

C. The Need for Continuity

1. The federal role

The federal role in advanced technology can never be in near term, industry-affordable, research and development. Government activities cannot respond rapidly to quickly changing demands, except in the most dire of crises, and

certainly cannot and should not compete with industry in meeting obvious market demands. Government activities can best address long-term, high-risk, potentially high payoff efforts that can benefit the U.S. economy as a whole. These activities can address and nurture decade-long or multidecade-long efforts to achieve major advances--and in the process develop and sustain an institutional memory that a private industry could not afford.

2. Long-term programs

In advanced space technology there are enormous voids that cannot be filled by even magnificiently funded programs that last only a few years. To be convinced, one needs only examine the mechanisms that limit the lifetime of any aspect of a spacecraft--whether in the "bus" or in the payload. With extraordinary rapidity one reaches the limits of knowledge as a variety of subtle life-limiting mechanisms are identified and schemes for their correction posed. The experienced space systems engineer quickly lists phenomena in bearings, batteries, radiation effects, cathodes for traveling wave tubes, microelectronic circuits, and a host of others where huge gaps in understanding exist. In every instance, if it is agreed that such gaps must be filled, the solution is never--or should never be assumed to be--a brief and casual foray into elementary science or technology. It is exactly these very tough, unyielding problems that OAST can address.

3. High-risk programs

A federal laboratory must always test the limits and undertake the high-risk project that is outside industry's acceptable range. Alvin Weinberg stated it very well when he wrote:*

... but unless we have technical failures as well as technical successes, we are not probing the limits of technology far enough. As long as the entire enterprise is showing healthy progress, we can take some failures in stride. The need for some research environments that encourage technological risk and adventure is one of the justifications for the national laboratories. We need institutions whose survival is not always a pressing issue and which, therefore, can try the hard as well as the safe projects. An important difference between national and private laboratories is that the national laboratories are buffered from the most acute pressures of survival to a greater degree than are private industrial laboratories. The resulting environment

* Alvin M. Weinberg, Reflections on Big Science, MIT Press, 1967

encourages the national laboratories to take greater technological risks than can private, single-purpose laboratories. This environment is an important national asset which I believe must be preserved.

It seems patently obvious that these words should apply to what OAST should represent within NASA and within the United States space technology community at large.

4. Career ladders and personnel development

Viable, self-sustaining organisms have a continuing influx and outflow and an internal cellular life cycle. The research environment must create a similar flow. The institution must have the continuity that attracts the strong leadership and promotes the development and evolution of junior researchers into group leaders into laboratory chiefs and so on. Continual disruption, change, or complete interruption produces a sterile environment and overwhelming waste--better to have no research than to have only the wasteful efforts carried out in such an environment.

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The development and growth of junior researchers requires fundamentally three factors: (1) exemplars they can emulate and learn from, (2) a stimulating environment where excellence is demanded and measured against the highest professional standards in a field, and (3) a focus by the parent organization on present achievement of scientific and technical results--rather than on an unending justification and rejustification of what is proposed to be done in the future once approval is gained.

Career growth by researchers requires time. Modern technology is complex, and the skills needed to advance it are not developed quickly or easily. Abrupt or continual changes cannot be permitted to disrupt the development of skills, if a commitment is made to achieving long-term and significant advances.

5. Critical mass and organizational synergism

The concept of critical mass is as useful in characterizing a research organization as it is for describing a chain reaction. The lone researcher, without colleagues or supporting staff, can still play a role in science, but only with extreme difficulty--and probably equally great inefficiency--in advancing modern space technology. Interdisciplinary projects require diverse skills, and researchers require the stimulation of others with similar interests; both requirements lead to the need for clustering numbers of researchers in close proximity. The assembly of such skills and the development of effective working

relationships require time to evolve and again a continuity of program.

Equally important is the synergistic effect of bringing research groups together. Isolated--in spite of the best management intentions to maintain coordination--small groups at, for example, Langley, Marshall, and Ames can never be as effective as a consolidated group that derives both the normal benefits of improved management effectiveness and the synergistic effects that result from a greater number of intellects interacting with one another. Largely unquantifiable, this effect is obviously very significant.

6. Facilities

For purposes of this section, facilities are intended to encompass the laboratories, computers, and computer software necessary to carry out research. The cost of all of these items prohibits NASA or OAST from maintaining first-rate facilities for a discipline at multiple locations. Every discipline has unique experimental, computational, and frequently used software or other elements that must be expanded, modified, serviced, or simply changed as equipment becomes obsolete and impossible to repair. This is a difficult overhead to support and a source of much current difficulty to university schools of engineering and science. Again the development of major capabilities--and particularly capabilities that will attract top talent--requires time and continuity.

D. Institutional Prestige and Attracting Talent

The title of this section is a redundancy. What leader can be attracted to fill the position of Section Chief of the third of five NASA sections devoted to research on spacecraft control systems? What person can be attracted to fill the position of Director of the NASA Spacecraft Control Systems Laboratory? The example is, perhaps, fictitious--but the principle is not. What's in a name? When it comes to attracting top talent, it may be a very great deal indeed. Names can obviously be deceptive, but if they are accurate they can carry weight and even produce an organizational momentum of a most healthy variety. Note that in the example used above two words were used: NASA and laboratory. Even though the organization is housed by a Field Center, it must carry authority across NASA and beyond; therefore, it is a NASA laboratory and not a Marshall or Goddard laboratory. This carries a message, just as evoking the name of "laboratory" carries a different message than section, branch, or division.

E. Harnessing Bureaucratic Dynamics

The "Bureaucracy" is a favorite target for nearly everyone. Yet bureaucracies can have positive qualities if properly harnessed. Among them are the development of consistent procedures for a variety of standard activities, so that procedures do not have to be reinvented each time they occur. This can add efficiency to such processes as preparation of publications, procurements, peer review, etc. They can also develop an organizational point of view and when things are done well an organizational esprit de corps. The natural tendency of a bureaucracy, whether administrative or scientific, is to expand and grow; there is no fundamental principle that this tendency cannot be directed toward the expansion of scientific skills and organizational capabilities.

F. Centers of Excellence Versus Lead Centers

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A number of years ago, NASA embarked on an experiment in "Lead Centers" that many regard as misguided and disastrous. Those memories will be hard to squelch, and it is important to note that the comments in this paper are not intended in any respect to encourage a return to the Lead Center concept. To illustrate the point, it is only necessary to recall the use of Marshall Space Flight Center as the Lead Center for communications research and development. All of the effort and skills existed at Goddard Space Flight Center, Lewis Research Center, and the Jet Propulsion Laboratory. None of the skills existed at Marshall. Being responsive to NASA Headquarters, Marshall promptly began building a staff of administrators, secretaries, and nonspecialist engineers to manage the other Centers' programs on behalf of Headquarters. In no sense was a "Center of Excellence" created--indeed quite the contrary, only an extra bureaucratic layer.

III. ORGANIZATIONAL CONSIDERATIONS

A. Relationship to the Parent Center

A Center of Excellence must be sustained and supported, and most particularly valued, by its parent Field Center. Field Center management must endorse strongly the presence of such an activity, for unenthusiastic tolerance is almost as fatal as overt opposition. The Field Center's Director must embrace the role the laboratory plays outside of the parent Center. In the absence of these ingredients, no attempt should be made to establish a laboratory at the Field Center.

B. Relationship to Other Field Centers

Nothing in this document should be construed to say that each and every venture in which the laboratory is involved must be carried out on the premises of the laboratory. This is as true for cooperation with other NASA Field Centers as it is for the cultivation of sound relationships with the military, industry, and academia. The comments in the preceding sections refer to establishment of a center of gravity and a critical mass, not to the elimination of all related activities in other Field Centers.

C. Program Development

The development of the program outline to be implemented by a laboratory, particularly one that purports to meet national, federal, and private needs, cannot be left to an in-house group alone. And particularly, it cannot be constructed by an in-house group going off to a retreat hideaway and bringing back the program like Moses from the mountain. In the following few paragraphs, a process will be suggested. The spirit of the process is vastly more important than the details. This is the nominal process that was employed in the attempt to restore the communications research and development program in NASA--and has met with reasonably wide approval.

Assume that candidate discipline areas have been identified. This might be done with a suitably chosen outside advisory group operating in close cooperation with NASA.

As an initial step, a distinguished panel of experts could be convened, also under the auspices of the advisory panel. In the instance of communications, this was the so-called Davenport Committee.* The task of the panel is to explore rigorously the boundaries and needs of the discipline and to identify the general directions that might be pursued by OAST. This is a formidable task and requires the best brains the United States has to offer. The panel must also have the freedom to determine that there is no role for OAST--if that is the appropriate answer.

As the next step, NASA should form a small team (five might be a reasonable number) of its best talents to take the recommendations of the panel and develop the next level of detail for research in the discipline. That team should physically visit every major laboratory and institution involved in the discipline (private, military, and federal) and obtain the opinion of every major worker in the discipline.

* Committee on Satellite Communications, National Research Council, "Federal Research and Development for Satellite Communications," 1977.

This could entail a hundred or more facilities and a much greater number of people. At each location they should communicate the conclusions of the panel and solicit the advice and comments of the active workers in the field. From this initial process, a near consensus is likely to result and should be formulated into a draft research plan that should be immediately--without further NASA review--sent back to each person visited and to the panel. This is a process of saying, "This is what we think you said to us, and these are the conclusions that we have reached. Is this what you meant and do you agree with our conclusions?" After incorporation of the comments, the plan should be presented to the panel for approval. After that point, it is ready for review by NASA management. It may or may not involve the identification of the recommended parent center for a proposed NASA laboratory, but that issue must be solved near this time.

If the plan meets the resource profiles of NASA and is consistent with NASA's intended direction, it can then be approved and, if necessary, proposed to the Office of Management and Budget and later to the Congress. Such a process ensures sound technical objectives and, not insignificantly, a fair degree of mobilization of the technical community behind the effort. It also begins the essential process of establishing the communication links and bridges to the outside community that the mature laboratory will need.

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D. Annual Review and Peer Review

The above process can only initiate a program, it cannot sustain its excellence. In the case of the communications program, some of the original Davenport Committee members continued to provide advice and guidance and, with others, eventually became the Harrington Committee during the above process. Well into implementation, this new Committee provided a healthy oversight of the ongoing program development.

A laboratory must be forced to survive in the full, bright light of review and scrutiny by peers. It must never, for example, fall back on calling limited distribution internal documents "publications" instead of reserving that term for refereed publications in the proceedings of the major societies. If it does produce internal publications for widespread use in the discipline, they must be as rigorously reviewed as the publications of the best societies. One approach to avoiding organizational entropy, could be a thorough annual review of all aspects of the laboratory, including an evaluation of the laboratory's productivity and progress in the discipline. A body to conduct such a review could be a "Board of Governors" for the laboratory, perhaps modeled after the activities of the Harrington Committee.

E. Board of Governors

No laboratory can afford to become complacent. No laboratory can be permitted to be satisfied by meeting only local or internal standards. A national investment in a laboratory to advance space technology deserves the best, most critical scrutiny that can be mounted. A Board of Governors made up of the best brains in the discipline who are not members of the laboratory or the parent Field Center--chosen from industry, academia, and the government--can ensure a laboratory's continued evolution and provide a none-too-subtle pressure for excellence. Continuity on the part of the Board of Governors produces benefits analogous to those quoted above for laboratories. Continuity of effort brings deeper and more penetrating insights into the operations, successes, and failures of the laboratory.

IV. IMPLEMENTATION

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If the suggestions made above were to be implemented, the difficulties would be great and considerable organizational learning and relearning necessary. The roles of the Headquarters Program Managers, the Field Center Director, and the directly affected personnel would all be radically different than what they are today. The Headquarters Program Managers would not have the authority and freedom of action they currently possess, for example. Therefore, any implementation should be deliberate, careful, and treated as an experiment in its own right. A single initial test case should be employed, with all conditions made as favorable as possible. Progress should be carefully monitored and the approach adjusted in light of the experience gained. Only after the initial errors have been made and corrected--and they would inevitably occur--should the effort be expanded to another test case. The potential rewards are great, but easy to destroy in infancy. As momentum developed and genuine successes accrued, it would only then be appropriate to carry out widespread use of these concepts.

V. ACADEMIC RELATIONSHIPS

This section and the succeeding ones address three vital relationships for a center of excellence--ties to the academic, military, and industrial communities. The first will be discussed here.

There are a number of ways a federal laboratory can establish ties to academia: (1) as a source of grants, (2) as a source of longer-term support through cooperative agreements, and (3) in active partnership that may even include staff and facility sharing. The existence of a center of excellence can assist making the closer of these relationships possible, particularly when a major university is adjacent to the federal facility.

The benefits flow both directions. The laboratory benefits from the wider spectrum of inputs it receives from the university staff. It may serve as a place where graduate students complete their research requirements for their degrees, and the students in turn represent a ready source of trained personnel for employment by the laboratory. Faculty members may also participate directly in the research of the laboratory. The laboratory benefits from the additional skilled personnel and the researchers gain access to more advanced facilities and projects than the university can provide--and carry the benefits of that access back to their classrooms.

Another aspect of joint activity is epitomized by the Resident Research Associate (RRA) program or other visiting scientist programs. These programs are extraordinarily successful when the RRA is integrated into a clearly defined program that has a sustained continuity of direction. Continuity is important because preparations begin years in advance of an appointment and the appointment may span two years. The program is ineffective when the RRA enters an uncertain program and must create both the program and the facilities to carry out his or her research.

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All of the above considerations can contribute to the evolution of a laboratory into an internationally recognized force in its discipline. The influx and outflow vital to growth and vitality mentioned earlier is augmented by the academic ties. These same ties will also contribute to the equally valuable industrial ties.

VI. INDUSTRIAL RELATIONSHIPS

It is important to distinguish between the relationship of a center of excellence to industry and that of the usual NASA organization. The normal relationship is that of a customer--as opposed to one in which NASA is necessarily a professional equal, with contributions to make to industry. While not intending to demean the capabilities of many NASA organizations, in too many instances the scale of expertise has tipped too far in favor of industry. In the broader context of NASA beyond that of only OAST, NASA's expertise in carrying out its role in project management may be damaged if the contractor's capabilities too far outpace those of NASA. Certainly, the existence of centers of excellence can contribute to redressing that imbalance.

In the conventional role of providing contracts, the relationship between federal and industrial personnel can be tainted by the normal competition for those contracts. While this must always be of concern, and a Center of Excellence would still have a role in managing extensive research contracts, the essential difference is that the personnel in a center of excellence would maintain skills equal to those of industry. Further, even though industry involvement would be a vital element in the activities of the laboratory, it would be the in-house personnel who would provide the continuity and retain the organized repository of skills and data. While a given industrial

involvement may come and go, the laboratory would maintain the program's integrity. The relationship with industry would be analogous to that maintained by NASA's predecessor organization, the NACA, and in some respects OAST's aeronautics centers.

An important role a federal laboratory may play is sharing the results obtained in its program, both in-house and under contract or grant. In the communications program, the vehicle of periodic meetings and workshops open to all interested parties proved to be a successful way to exchange information. Conducted like those of any professional society, presentations were followed by vigorous question and answer sessions. These were widely approved and their continuation encouraged by industry.

There is a normal tension between the fraction of work carried out by the in-house staff (including visiting scientists or professors sharing the facility) and that carried in industry. Certainly a large fraction of the work should be done in industry. The exact fraction will be a function of the particular discipline and the research planned. Rather than attempting to solve a problem here for which there is no general solution, suffice it to note that this subject must be included in the initial detailed planning of the program.

VII. DoD RELATIONSHIPS

There are a number of obvious steps that must be taken to coordinate work being done in a center of excellence with that of DoD. One of those steps is to assure that the Laboratory Director has an appropriate security clearance and established need-to-know. This may not seem like much of a step--yet it is not done today in many instances. Instead, coordination is carried out by distantly removed offices with a corresponding communications loss. The thrust of the recommendations given above on the creation of a Center of Excellence is to create a knowledgeable management with personal ties to the entire community for that discipline; this must extend equally to DoD.

Another step is active participation by laboratory people in the review by DoD of industry's IR&D. Properly supported, this can provide many valuable insights.

A further step is arranging for the assignment of military scientific and technical personnel to the laboratory. Rotating assignments for both research or liaison are equally valuable in establishing and maintaining the ties that are necessary.

These working level contacts can be overlaid with high-level coordinating boards for broader policy issues, but the higher boards cannot substitute for the working-level associations.

VIII. CONCLUDING REMARKS

The above observations lead to the following recommendations:

1. The balance between applied research to satisfy institutional needs and that to make major advances in space technology should be made by explicit management decision.
2. OAST cannot make significant advances in space technology without focusing its financial and organizational resources in a few selected disciplines.
3. Centers of Excellence, carrying the title of the NASA "Laboratory for" should be established in Field Centers for the selected disciplines.
4. Program continuity must be assured to address the long-range, high-risk programs appropriate to a federal laboratory; to provide career development; to aggregate the cohesive group of professional skills to reach scientific critical mass; to develop the facilities required for modern research; and to create the institutional prestige that will attract top talent and vice versa.
5. A Center of Excellence is a NASA-wide activity housed by a Field Center with responsibilities to the space technology community at large. Unless this is an attractive idea to the Field Center Director, it should not be initiated there.
6. The development of the program for a Center of Excellence must be carried out through an iterative process involving the best experts from private industry, academia, and the government. It must not be done in isolation.
7. Every opportunity must be taken to force a Center of Excellence to exist under intense scrutiny. Annual reviews, peer reviews, and a Board of Governors are possible ways to create that scrutiny.
8. Establishing Centers of Excellence should be a one-at-a-time controlled experiment--and not a wholesale implementation.
9. Vigorous, continuing, working-level relationships and partnerships must be maintained with private industry, academia, and DoD.

Appendix E

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Communications:

American Satellite Corporation
American Telephone & Telegraph Co.
Crawford Hill Laboratory
Communications Satellite Corporation
GTE Satellite Corporation
Satellite Systems Engineering
Satellite Television Corporation

Earth Observation:

Earth Satellite Corporation
Geosat Committee
U.S. Army Corps of Engineers
U.S. Geological Survey

Weather:

National Earth Satellite Service
National Weather Association

Navigation:

Ocean Routes, Inc.

Materials Processing:

Deere & Co.
Johnson & Johnson
Pickering Research Corporation

Other:

Universities Space Research Association
Public Services Satellite Consortium

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SPACE SYSTEMS MANUFACTURERS:

Ball Aerospace Systems Division
Boeing Aerospace Company
Fairchild Industries, Inc.
Ford Aerospace & Communication Corporation
General Electric Company
Gruman Aerospace Corporation
Lockheed Missiles & Space Co., Inc.
McDonnell-Douglas Astronautics Co.
RCA Astro-Electronics
North American Space Operations
TRW Defense & Space Systems Group
Aerospace Division, Westinghouse Electric Corp.

SPACE COMPONENT AND DEVICE MANUFACTURERS:

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Optical Coating Labs, Inc.
Hughes Aircraft Company
Santa Barbara Research Center
Hughes Aircraft Company
Spectrolab
Hughes Aircraft Company
H.R. Textron, Inc.